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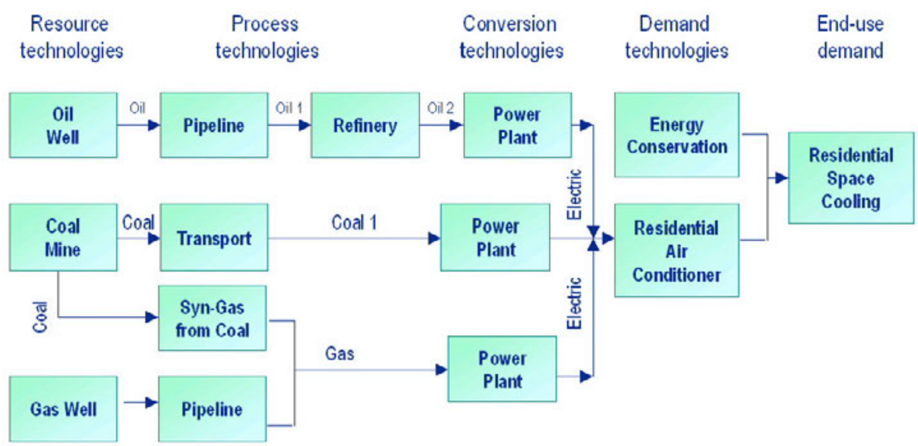
Demonstration of a Scenario Approach for Technology Assessment: Transportation Sector



Typical MARKAL Reference Energy System

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Demonstration of a Scenario Approach for Technology Assessment: Transportation Sector

by

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Abstract

EPA's Office of Research and Development (ORD) is pursuing an Air Quality Assessment that will examine the potential consequences of global change on tropospheric ozone and particulate matter in the year 2050. Technological change is one of the most important drivers for the future of environmental air quality and global environmental change. The National Risk Management Research Laboratory's Technology Assessment and Co-control Team (TACT) is pursuing a scenario-oriented approach to the assessment of future technologies and patterns of technology adoption in the transportation and electricity generation sectors. This report presents TACT's approach and highlights early results in the transportation sector. Scenarios considering advanced internal combustion engine vehicles, hybrid vehicles, and hydrogen vehicles and their associated fueling infrastructures are developed and analyzed. Preliminary emissions modeling results suggest different technology development and penetration scenarios may have greatly differing emissions consequences and, hence, differing air quality implications in the Air Quality Assessment time horizon. Future work will further develop the analysis of the transportation sector, including an assessment of the interaction between economic and technological changes, and will expand to include an analysis of the electricity generation sector.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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Sally Gutierrez, Acting Director
National Risk Management Research Laboratory

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Table of Contents

Table of Contents (concluded)

List of Figures

List of Figures (concluded)

List of Tables

Acronyms and Abbreviations

Term	Definition
2XH	scenario in which hybrid vehicles get twice the gas milage as conventionals
AC	alternating [electrical] current
ACEEE	American Council for an Energy Efficient Economy
AEO	Annual Energy Outlook, a DOE publication
ANL	Argonne National Laboratory
API	American Petroleum Institute
C	Elemental carbon
CAA	Clean Air Act
CCRI	Climate Change Research Initiative
CD	scenario in which conventional vehicles dominate the market
CH_4	methane
CIDI	compression ignition direct injection
CMAQ	Community Multiscale Air Quality
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CPPD	Climate Protection Partnerships Division
DC	direct [electrical] current
DOE	U.S. Department of Energy
EAU	evolution as usual scenario
EDF	Environmental Defense Fund
EE/RE	Energy Efficiency/Renewable Energy
EGAS	Economic Growth Analysis System model
EIA	Energy Information Administration
EMPAX	Economics Model for Environmental Policy Analysis [EPA model]
EPHE	early phase hydrogen economy scenario
EPRI	Electric Power Research Institute
ETSAP	Energy Technology and Systems Analysis Program
FCHV	fuel cell hybrid vehicle
FCVs	fuel cell vehicles
GHE	green house equivalents
GHG	greenhouse gas
GIS	Geographic Information System

continued

Acronyms and Abbreviations (continued)

Term	Definition
GJ	Gigajoule
GP	scenario in which gas price varies
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
H_2	hydrogen
H2A	DOE's hydrogen Analysis workgroup
H2F	scenario in which conversion to hydrogen powered vehicles is forced
H2M	scenario with moderate H_2 FCV market penetration
H2O	scenario with optimistic H_2 FCV cost and efficiency assumptions
HC	hydrocarbon
HEVs	hybrid electric vehicles
HM	scenario in which hybrid vehicles are incorporated into the market
HM(C)	scenario in which hybrids drive conventional vehicles from the market
ICE	internal combustion engines
IPM	Integrated Planning Model
LBNL	Lawrence Berkeley National Laboratory
LEV	low emissions vehicle
LP	linear programming
LPG	liquefied petroleum gas
MARKAL	MARKet ALlocation computer model
MGA	Modeling to Generate Alternatives
mpg	miles per gallon
NCER	National Center for Environmental Research
NEMS	National Energy Modeling System (U.S. EIA)
NERL	National Exposure Research Laboratory
NETL	National Energy Technology Laboratory
NO_X	nitrogen oxides
NRMRL	National Risk Management Research Laboratory
NRSA	Nominal Range Sensitivity Analysis
OAQPS	Office of Air Quality Planning and Standards
ORD	Office of Research and Development
OTAQ	Office of Transportation and Air Quality
OTT	DOE's Office of Transportation Technologies
PEM	proton exchange membrane
PJ	pentajoules
PM	particulate matter

continued

Acronyms and Abbreviations (concluded)

Term	Definition
PM_{10}	PM with aerodynamic diameter 10 µm or less
$PM_{2.5}$	Fine PM with aerodynamic diameter 2.5 µm or less
POX	partial oxidation [reformer]
psig	pounds per square inch gauge
QM	Quality Metrics
R&D	research and development
REMI	Regional Economic Models, Inc. (economic model)
RES	reference energy system
RFF	Resources for the Future
RTI	Research Triangle International Institute
SAGE	System for the Analysis of Global Energy Markets
SMR	steam/methane reforming
SULEV	super ultra-low emissions vehicle
SUV	sports utility vehicle
TACT	Technology Assessment and Co-control Team
TAG	Technical Assessment Guide
ULEV	ultra-low emissions vehicle
USGCRP	U.S. Global Change Research Program
VMT	vehicle miles traveled
VOCs	volatile organic compounds

Executive Summary

The Office of Research and Development (ORD) is pursuing an Air Quality Assessment that will examine the potential consequences of global change on tropospheric ozone and particulate matter (PM) in the year 2050. In developing this assessment, it is recognized that technological change is one of the most important drivers for the future of environmental air quality and global environmental change. Within EPA, the Technology Assessment and Co-control Team (TACT) of the National Risk Management Research Laboratory is chartered with providing potential trajectories for technological evolution to ORD's Air Quality Assessment. Rather than defining a "best guess" future, TACT is pursuing a scenario-oriented approach to the assessment of future technologies and patterns of technology adoption, with a focus on the transportation and electricity generation sectors. This report presents TACT's approach and highlights early results in the transportation sector. Future work will develop the analysis of the transportation sector further, including an assessment of the interaction between economic and technological changes, and will expand to include an analysis of the electricity generation sector.

Approach

The primary focus of TACT's analysis is examining technological change in transportation and energy generation because these are the economic sectors that are thought to have the greatest effect on ambient air quality. Transportation and electricity generation cannot be studied in isolation, however, since there are important interactions both between these sectors and the rest of the economy. Many of these interactions are related to the supply and demand of various forms of energy. To model the U.S. energy system, TACT is using the MARKet ALlocation (MARKAL) model (Seebregts et al., 2001), a well-established energy system model. MARKAL is a bottom-up, linear, optimization-driven model that is easily distributed, non-proprietary, widely used, and has an active user community. The model provides a framework for organizing performance, cost, use, and constraint data for all current and future technologies in the energy system being modeled. Scenarios representing plausible storylines can be tested in MARKAL by modifying appropriate input parameters. A set of scenarios assists in the understanding of possible future technological change.

The approach for performing technology assessments involved several phases. The first phase required developing the reference energy system (RES) in MARKAL. The RES is a technology-rich database representing the economic sectors in the U.S. energy system. The sectors which have been completed include resource supply, commercial, residential, transportation, and electricity generation. The industrial sector is currently represented by a fixed fuel demand, but work is nearly complete that will characterize this sector more completely.

The U.S. Department of Energy's (DOE) Annual Energy Outlook (AEO) was used to construct the energy supply, demand, and technology data that made up the RES. The AEO data were derived from the U.S. Energy Information Agency's (EIA) National Energy Modeling System (NEMS) (U.S. EIA, 2003a) and are a nationally recognized source of technology data. Where AEO data were not available, RES data were derived from other widely recognized authoritative sources (e.g., Electric Power Research Institute's Technical Assessment Guide and DOE's Office of Transportation Technology's Quality Metrics report). In addition to defining technology parameters, emission factors have been gathered for the RES technologies (e.g., EPA's Air Quality and Emissions Trends Report). In every case, including the use of AEO data, the data source has been well documented with the original data source readily available to those of interest.

Data in the completed sectors were assessed by sector appropriate reviewers. The assembled model was then calibrated to the results of AEO 2002 (U.S. EIA, 2001). Once the industrial sector has been completed, full calibration results from the RES will be peer-reviewed by MARKAL modelers.

The transportation sector, the area of focus for this phase of the analysis, was then supplemented with data characterizing potential developments in future technologies. Initial efforts address technological change in five classes of personal vehicles—compacts, full-size, minivans, pick-up trucks, and sport utility vehicles (SUVs)—and the associated fuel-producing technologies. For this report, data gathering focused on hybrid vehicles, hydrogen fuel vehicles, and the technologies required to provide a hydrogen infrastructure. For all these technologies, literature searches have been performed to establish a range of estimates for key MARKAL parameters such as efficiencies and capital and operating costs. At this time, gasoline and methanol fuel cells and both biofueled cars and their associated biofuel-production pathways are still being investigated and are not included in this report.

The next phase of the work involved characterizing "storyline" scenarios, and applying the MARKAL model to generate results in response to each. In this context, scenarios are not predictions of the future. Rather, each scenario is an alternative and internally consistent depiction of how the future may unfold, given assumptions about future economic, social, political, and technological developments. A scenario-based approach is particularly appropriate for assessments involving a long time horizon, such as technology assessments linked to future air quality. Results from a selected set of these scenarios will serve as input to the ORD Air Quality Assessment.

Scenarios Investigated

For this report, several scenarios have been investigated along two possible technological futures: (i) evolution as usual (EAU) and (ii) early phase hydrogen economy (EPHE). The EAU scenarios propose continued advancement of conventional internal combustion and hybrid transportation technologies, and the EPHE scenarios investigate possible transformations to a hydrogen-based economy in transportation.

Five primary EAU scenarios were investigated: (i) Conventional Internal Combustion Vehicles (Conventionals) Dominate, (ii) Hybrid Market, (iii) Double Efficiency Hybrids, (iv) Gas Price Variation, and (v) Hybrid Market Without Conventionals.

Conventional Internal Combustion Vehicles (Conventionals) Dominate—In this scenario, both high efficiency internal combustion engines (ICE) and hybrids play a negligible role in meeting transportation demand. The primary Conventionals Dominate (CD) scenario applies a 7 percent "hurdle" rate premium—which reflects the reluctance of the market to change to a new technology—on hybrids and conventionals with increased efficiency. Other associated scenarios that could minimize penetration of advanced technologies include higher capital costs for advanced technologies and lower gasoline prices than presently anticipated. Both scenarios would favor the status quo.

Hybrid Market—This scenario foresees a moderate penetration of hybrid vehicles of 10 to 15 percent in 2030. Two hybrid technology options are available representing two levels of efficiency advancements. The success of hybrid vehicles will depend largely on their cost and performance relative to ICE powered vehicles, consumer attitudes regarding new technologies, manufacturing capacity, and fuel costs. Hybrid market penetration in the MARKAL model scenarios is thus a function of hybrid capital costs and operating efficiencies, the particular discount (or hurdle) rate applied to the technology, growth constraints on hybrid penetration, and gasoline prices. A primary Hybrid Market scenario incorporates growth constraints to capture the inertia of consumers moving from conventional internal combustion vehicles to a new technology and the slow pace of assembly line retooling. Two associated scenarios investigate the impact of a 10 percent reduction in hybrid capital cost (roughly equivalent to the present day tax credit) and of a 16 percent increase in capital cost for advanced efficiency conventional internal combustion vehicles, a primary competitor of hybrids.

Double Efficiency Hybrids—In the MARKAL database, hybrids are represented in two technology categories, one with twice the miles per gallon (mpg) efficiency (2X) of conventional internal combustion vehicles and the other with three times the miles per gallon (3X) of conventionals. The Double Efficiency Hybrid scenario examines penetration where hybrid development does not achieve the higher efficiency levels.

Gas Price Variation—The greater efficiencies of hybrids will yield long-term savings in fuel costs. Thus, their attractiveness relative to standard ICE vehicles might be expected to increase with the price of gasoline. The Gas Price Variation Scenario looks at the impact of a gasoline cost about three times higher than the current average price on the penetration of hybrids. While this value is high for the U.S. market, it is close to present European costs.

Hybrid Market Without Conventionals—It is conceivable that, with proven reliability and reasonable cost, hybrid engines become the new conventional transportation technology. The EAU Hybrid Market Without Conventionals [HM(C)] Scenario, therefore, examines the impact of phasing out (via a model constraint) all conventional vehicles in 2025.

Besides the EAU scenarios, futures associated with EPHE were analyzed in MARKAL. The primary EPHE scenarios are: (i) Hydrogen Market, (ii) Optimistic Hydrogen Market, and (iii) Hydrogen Forcing.

Hydrogen Market—This scenario looks at a future of about 10 percent penetration of hydrogen fuel cell vehicles (FCVs). In this scenario, hydrogen FCVs are competitive with hybrids. Larger class FCVs become available in 2015, while compacts become available in 2020.

Optimistic Hydrogen Market—The scenario assumes that, with sufficient funds to support research, cost effective solutions can be found for hydrogen storage and for manufacturing cheaper fuel cell stacks. Success in the fuel cell vehicle market encourages implementation of the necessary infrastructure, speeding the transition to a hydrogen economy. The Optimistic Hydrogen Market (H2O) scenario investigates this by using optimistic values for FCV costs and efficiencies.

Hydrogen Forcing—It may be that movement to a hydrogen economy is led by actions which seek to improve air quality by requiring specific penetrations of environmentally friendly technologies, such as FCVs. The Hydrogen Forcing (H2F) scenarios investigate penetrations at 2030 ranging from 10 to 50 percent.

Results

Table 1 presents the results of the primary EAU and EPHE scenarios where results are ordered by increasing penetration of hybrids for the EAU scenarios and by increasing penetration of hydrogen FCVs for the EPHE scenarios. With the exception of the Double Efficiency Hybrid scenario, the majority of the hybrid technology penetration by 2030 is from the 3X technology. As shown in this table, for the EAU scenarios, hybrids have significant penetrations under a scenario of high gas prices and when there is a fundamental market change away from conventionals.

Table 1. Technology Penetrations in 2030 for Evolution as Usual and Early Phase Hydrogen Economy Scenarios.

Scenario	Conventionals %	Hybrids %	FCVs %
EAU			
Conventionals Dominate	100	0	0
Hybrid Market	87	13	0
Double Efficiency Hybrids	85	15	0
Gas Price Variation	36	64	0
Hybrid Market Without Conventionals	3	97	0
EPHE			
Hydrogen Market	83	8	9
Optimistic Hydrogen Market	80	6	14
Hydrogen Forcing	46	4	50

For the EPHE scenarios, hydrogen FCV penetration is only significant by 2030 under a forcing scenario. Without forcing, penetration is less then 15 percent even when optimistic costs and efficiencies are assumed for the FCVs. These rates are partially explained by FCVs not being available until 2015, leaving only 15 years for market penetration. In moving to hydrogen FCVs, market share is taken both from the hybrids and conventionals.

The impacts of the EAU and EPHE technology penetrations on transportation sector emissions are shown in Table 2. Significant reductions are observed for scenarios with high penetrations of hybrids and/or hydrogen FCVs.

Table 2. Emission Reductions in 2030 for Evolution as Usual and Early Phase Hydrogen Economy Scenarios Relative to Conventionals Dominate.

Scenario	PM_{10}[a] %	CO[b] %	NO_X[c] %	VOCs[d] %
EAU				
Hybrid Market	15	<1	5	10
Double Efficiency Hybrids	16	<1	5	11
Gas Price Variation	58	3	41	35
Hybrid Market Without Conventionals	89	7	70	50
EPHE				
Hydrogen Market	19	10	9	25
Optimistic Hydrogen Market	22	15	12	32
Hydrogen Forcing	55	50	50	59

[a] PM_{10} = PM with aerodynamic diameter ≤ 10 µm.
[b] CO = carbon monoxide.
[c] NO_X = oxides of nitrogen.
[d] VOCs = volatile organic compounds.

Conclusions

A scenario approach for technology assessment has been developed and demonstrated for several future technologies in the transportation sector. The modeling approach adopted here allows the rapid assessment of varying assumptions about the factors that influence technology penetration. Although the emissions modeling presented here is preliminary, the scenarios considered indicate that different technology development and penetration scenarios may have greatly differing emissions consequences. Consideration of a broad range of technology scenarios is, therefore, essential for a thorough evaluation of the potential impacts of climate change on air quality.

Additional work is required to produce a full scenario analysis of the transportation and electricity generation sectors out to 2050. This future work includes:

- continued database development and extension to 2050,
- documentation and release of the database,
- improvements to the representation of the transportation and electricity sectors,
- evaluation of approaches for incorporating economic interactions,
- development of a set of alternative technology futures,
- sensitivity and uncertainty analysis, and
- integration with the ORD Air Quality Assessment.

Section 1
Technology Assessment and Project Scope

1.1 Background

In 1990, the United States Congress enacted the U.S. Global Change Research Act creating of the U.S. Global Change Research Program (USGCRP), which has the goals of "understanding and responding to climate change, including the cumulative effects of human activities and natural processes on the environment." (USGCRP, 1990) Thirteen government agencies are part of the program, including the National Science Foundation, the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration, the Agency for International Development, the Smithsonian Institution, and the Departments of Commerce, Energy, State, Interior, Agriculture, Health and Human Services, Transportation, and Defense. The activities of each of these agencies in support of the USGRCP are described on the USGCRP website. (USGCRP, 2004)

In 2001, the President announced the establishment of the U.S. Climate Change Research Initiative (CCRI). CCRI was developed to complement the USGRCP with the goal of supporting policy makers in the short term through "the integration of scientific knowledge, including measures of uncertainty, into effective decision support systems." To achieve this goal, CCRI is focusing on reducing the uncertainties in climate science and modeling, improving the monitoring and analysis of climate change signals, and improving resources for supporting decision-making. (USGCRP, 2001)

The EPA's primary role under these programs is to develop an understanding of the potential consequences of global change (and particularly climate variability and change) on human health, ecosystems, and socioeconomic systems in the United States. This information will support stakeholders and policy makers as they decide whether and how to respond to the risks and opportunities presented by global climate change. A central component of the EPA's activities is to examine the interactions between global climate change and air quality.

Global climate change will likely result in changes in regional and local weather. These changes in meteorology may affect air pollution levels by altering (1) rates of atmospheric chemical reactions and transport processes, (2) anthropogenic emissions, including adaptive responses involving changes in fuel combustion for power generation, and (3) biogenic emission rates from natural sources. To assess these potential changes, the Office of Research and Development (ORD) is pursuing an Air Quality Assessment that will explore the potential consequences of global change on tropospheric ozone and PM through the year 2050.

Within the last century, emissions resulting from human activities have contributed to increased ambient concentrations of tropospheric ozone and PM and have necessitated government environmental policies such as the Clean Air Act and its amendments (CAA). (CAA, 2002) Although the CAA is intended to improve air quality in the present and into the future, an unknown is the interaction between future emissions levels and the temperature and meteorological changes associated with global climate change. Making such an assessment requires the examination of a wide range of factors, such as changes in land use, population size and demographics, air pollution control technologies, and energy generation and use technologies. Since many of these factors are closely linked, a systems analysis approach may be most appropriate.

Within ORD, the National Risk Management Research Laboratory (NRMRL), the National Exposure Research Laboratory (NERL), and the National Center for Environmental Research (NCER) are collaborating to conduct the Air Quality Assessment. NERL will conduct regional air quality modeling for the year 2050 using the EPA Community Multiscale Air Quality (CMAQ) model with climate change inputs from regional climate model simulations. In order to perform this air quality modeling, an emissions inventory for the year 2050 must be prepared. This work will be done jointly by NRMRL and NERL. NRMRL's role in this collaboration is to identify future technological scenarios that will influence future emissions. NCER will be obtaining input data to the entire analysis and will be overseeing the modeling of climate change.

Many natural, economic, and technological factors must be considered in order to create scenarios of projected emission values. In particular, changes in the technologies that produce emissions can be expected to play a central role in driving future air quality. To increase the precision of environmental forecasts, it is important to improve the characterization of technological change. In this context, the National Research Council in 1999 (NRC 1999) identified characterization of the sources and processes of technological change as one of the seven key research pathways for the USGCRP's human dimensions of global environmental change research area.

NRMRL's Technology Assessment and Co-control Team is carrying out the assessment of technological change. Although technological change has played a central role in increased emissions, it does not exclusively produce negative impacts. New, cleaner technologies may ameliorate many current environmental problems or prevent future problems. For example, the emergence of hybrid and fuel cell cars is expected to offset emissions from increased transportation demand. Forecasting technological change, such as the penetration of hybrids and fuel cells as well as the emergence of newer technologies, is thus an important aspect of predicting environmental quality in the future.

Forecasting technological change is an inherently uncertain process, however. Technological change is driven by many factors, including economic change, research and development (R&D) level of effort and success rates, energy resource supply and price, consumer preferences, and policy changes, none of which can be predicted with certainty. Rather than defining a "best guess" future, TACT is pursuing a multidimensional, scenario-oriented approach to the assessment of future technologies and patterns of technology adoption. This scenario-based approach involves the development of a set of alternative, plausible futures that seek to characterize the range of possible realizations of the future.

TACT's work is focused on the transportation and electricity generation sectors since these are the largest contributors to criteria pollutants. Transportation accounts for about 50 percent of emissions of the ozone precursors nitrogen oxides (NO_X) and volatile organic compounds (VOCs) and 25 percent of fine particulate matter ($PM_{2.5}$). Electricity generation accounts for 25 percent of NO_X and about 6 percent of $PM_{2.5}$. (U.S. EPA, 2000) Both of these sectors are characterized by a wide array of possible future technologies with very different and uncertain environmental, economic, and social implications. Although there have been many reports from the national labs, university research programs, and trade groups on the future of technologies in these sectors, none of these assessments have systematically synthesized these many dimensions. Thus, the goal of TACT is to provide a comprehensive technological assessment, identifying future technological scenarios and facilitating the evaluation of these scenarios within ORD's Air Quality Assessment.

The time frame for completion of the Air Quality Assessment is 2010. TACT is in the process of finalizing a methodology and demonstrating this methodology with preliminary results. The methodology and preliminary results are being subjected to a peer-review process to ensure that the approach taken is practical and defensible. TACT is also working with other members of the ORD Air Quality Assessment team to plan and coordinate modeling activities.

This report presents TACT's approach for quantifying technological evolution and highlights early results in the transportation sector. The scenarios presented here consider the impacts of R&D developments, fuel prices, consumer preferences, and technology policies on the penetration of technologies within the personal vehicles subsector. Future work will further develop the analysis of the transportation sector, including an assessment of the interaction between economic and technological changes, and expand to include an analysis of the electricity generation sector. In addition, TACT will explore issues related to sensitivity analysis and characterizing the effects of uncertainty on forecasts of technological change.

1.2 Project Scope

Early on, TACT recognized that forecasting technological change in the transportation and electricity generation sectors could not be done successfully if these sectors were treated in isolation from the rest of the U.S. energy system. Competition from other sectors for the same fuel resource supplies can impact the viability of a new technology, and implementation of new technologies can have consequences in other sectors.

The potential penetration of new technologies is a function of both economic factors (e.g., supply, demand, and pricing) and non-economic factors (e.g., environmental benefits, local and national legislative actions, social and political concerns). Thus, in developing technological assessments, it is important to include some consideration of both categories of factors.

Finally, TACT realized that to adequately combine all these considerations, an approach must be defined which allows the identification and evaluation of a range of plausible futures. Several viable technological paths can be chosen from this set for use in the ORD Air Quality Assessment. These technological paths will be selected such that they represent the range of potential plausible outcomes and so that they are internally consistent with respect to assumptions about future economic, social, political, and technological developments. TACT will use a model of the U.S. energy system to develop these scenarios. The scenarios will characterize potential technological futures through the year 2050. In addition, TACT will develop and execute plans for examining the sensitivities of outcomes to various assumptions, as well as the effects of uncertainties on technological forecasts.

To model the U.S. energy system, TACT is using MARKAL, a well-established energy system model. MARKAL provides a framework, called the reference energy system (RES), for organizing performance, cost, use, and constraint data for all current and future technologies in the energy system being modeled.

Since MARKAL is a least-cost optimization model, it is capable of selecting those technologies that most cost-effectively meet demand and emissions constraints. This information is useful in identifying if or when in the future specific technologies are expected to penetrate their markets based on economic considerations. The effect of various assumptions and policies such as financial incentives can also be explored to evaluate their effect on the economics of new technologies. MARKAL also includes emissions data for relevant technologies. MARKAL modeling is discussed in more detail in Section 2.

Overall, the TACT team's objectives for MARKAL modeling include:

- developing the U.S. reference energy system representation in the MARKAL model,
- determining which future technologies will be considered for scenario analysis and gathering and incorporating the necessary MARKAL data,
- determining economically plausible future technology scenarios, and,
- determining the pollutant emissions from those scenarios.

Results of this work will be applied for two purposes. In the longer term, MARKAL outputs of technology penetrations will be used by other groups in ORD's Air Quality Assessment for the next phases of that work. In the immediate term, the scenario runs will be used to support discussions of the system-wide impacts of technology choices on emissions. In addition, the scenarios can be paired with other modeling works to help elucidate the plausible storylines that yield outputs comparable to those earlier works.

TACT's focus on characterizing technological change in the transportation sector will continue through 2004. Alternative fuels and vehicle designs will be investigated to determine their influence on emission rates, and the time profile for the market penetration of these technologies will be determined. Characterization of public transit and freight technologies will also be improved. For the outputs needed from this work in 2006, there will be a greater emphasis on electricity production. Changes/improvements in fossil fuel electricity generation, alternative electricity generation technologies, and market penetration of these technologies will all be examined and incorporated into emissions modeling.

The sections that follow delineate TACT's approach to technology scenario analysis and describe some early, illustrative results in the personal vehicles sub-sector:

- Section 2 describes the general approach used by TACT to model the U.S. Energy System. The section includes a more detailed description of MARKAL modeling, the approach to generating scenarios, and preliminary ideas related to conducting sensitivity and uncertainty analyses.
- Section 3 describes the work that has been carried out to characterize personal vehicle technologies and to forecast the use of these technologies through the year 2035.
- Section 4 focuses on efforts to incorporate hydrogen-powered fuel cell vehicles and the related infrastructure into the model. This discussion illustrates how new technologies can be integrated into the U.S. Reference Energy System.
- Section 5 applies the technologies described in Section s 3 and 4 to identify future technological scenarios. In particular, these scenarios examine factors that affect the adoption of hybrid and fuel cell powered personal vehicles.
- Section 6 presents MARKAL modeling results for the scenarios specified in Section 5. The discussion illustrates how MARKAL results can be interpreted to better understand the various interactions and drivers for technological change.
- Section 7 discusses future activities, including improvements to the representation of the transportation and energy sectors; extension of the database to 2050; continued database development, documentation, and release; the development of a set of alternative technology futures; and sensitivity and uncertainty analysis.

Two appendices are included to provide more details about various aspects of the project. Appendix A focuses on modeling with MARKAL, including a discussion of the MARKAL representation of the RES. Appendix B discusses MARKAL database development, peer-review, and calibration.

Section 2
General Modeling Approach Using MARKAL

This section provides an introduction to the MARKAL model. Topics that are discussed include an overview of economic models for air quality assessments, a description of MARKAL, a description of the development and calibration of an EPA U.S. MARKAL model, an overview of the scenario-based approach that is taken in MARKAL modeling, a discussion on the incorporation of future technologies, and a description of the assessment of the emissions consequences associated with technological change.

2.1 Economic Modeling for Air Quality Assessment

Economic models have been used extensively in the context of global climate change assessment. These applications typically have involved the projection of future green house gas emissions by modeling the effects of economic sector growth and anticipated technological changes. Weyant (2000) and Edmonds et al. (2000) provide reviews and comparisons of these applications. Economic models have also been used in regulatory applications. For example, the EPA's Office of Air Quality Planning and Standards uses data from the Regional Economic Models, Inc. economic model in conjunction with the Economic Growth Analysis System emissions projection system to forecast future emissions of criteria air pollutants. This approach has been applied to project emissions through the year 2020. In contrast, ORD's Air Quality Assessment must evaluate pollutant emissions through the year 2050.

A variety of factors differentiate the economic models used in climate change assessments. These factors include are discussed below.

<u>Representation of technologies (top-down or bottom-up)</u>—Bottom-up models explicitly represent energy-using technologies. Each technology is characterized by information such as capital costs, operations and maintenance costs, energy inputs, outputs to meet various demands, emissions, efficiency, and lifetime. A bottom-up model uses this information to make technological selections into the future based upon criteria such as cost-effectiveness and constraints on availability. Top-down models, in contrast, model supply and demand within and across economic sectors. These models often include assumptions about

technological improvement, but do not represent technologies explicitly. Top-down models can also include factors, such as household savings and investment in research and development, that typically are not incorporated into bottom-up models.

Scope (single-sector or multi-sector)—Some economic models may represent only one sector of the economy. For example, the Integrated Planning Model (IPM) represents only the electricity sector (Clean Air Markets, 2004). IPM is not able to capture the effects of electricity prices on non-electricity sector technological decisions. Further in contrast, some economic models represent multiple sectors or may even attempt to represent all relevant sectors. Representation of multiple sectors allows the interaction among those sectors to be evaluated.

Time horizon (short term or long term)—Models that have been used in regulatory applications often extend only to the year 2020 or 2030. Models used in the assessment of global climate change typically must have a much longer horizon, extending to the year 2050 or further.

Geographic resolution (global, national, multi-regional, or regional)—The geographical scale of economic models can differ greatly. For example, global models often represent the interactions among the economies of different countries but are not able to provide results at a sub-country level. In contrast, a national model may ignore economic interaction with other countries or may represent those interactions very simplistically.

Incorporating feedbacks on demands (static or elastic)—Economic models often produce estimates of energy prices (e.g., dollars per gallon of gasoline). In reality, changes in prices will likely result in changes in demand. Although top-down models are more likely to include such elasticity relationships, this information can also be incorporated into bottom-up models.

Problem representation (linear or nonlinear)—Economic models may be linear or nonlinear. Linear models represent the relationships among various factors in the model with linear equations. Nonlinear models allow much more complicated representations of interactions. Linearization has the potential to over simplify the modeled relationships, losing the ability to account for economies of scale and adding uncertainty to model predictions. Linear models have advantages, however; they are more readily solved, the results are often more transparent, and data collection requirements are simplified. Further, linear representation may not be worse than a nonlinear representation when the available data are not sufficient to provide a good characterization of the necessary nonlinear functions.

<u>Solution procedure (simulation or optimization)</u>—Economic models are typically either simulation models or optimization models. The goal of a simulation model is to describe some phenomenon, which is energy system behavior in this case. In the context of an air quality assessment, a simulation model would forecast future emissions. Optimization models, in contrast, are often used as prescriptive models. These models typically include an objective (e.g., minimize cost) and a set of constraints. A solution procedure is used to identify the solution that best meets these criteria. An optimization model might be used to identify what one should do (e.g., the technological mix that is expected to most cost-effectively meet an emissions reduction). It should be noted that optimization models potentially could be used in a descriptive sense by constraining the various decision variables. Also, the objective of minimizing cost can be interpreted as driving a simulation toward an economically feasible, cost-effective solution.

Given these various factors, TACT was interested in identifying a model with the following characteristics:

- a bottom-up approach such that technological changes can be characterized explicitly,
- the flexibility to be used at various national or regional scales,
- a flexible time horizon that facilitates use in ORD's global climate change air quality assessment,
- an optimization-based structure such that various objectives and constraints could be explored,
- a track record of successful applications,
- an active user community that could be tapped for feedback and support,
- a transparent structure in which assumptions and the processes driving analysis results are readily apparent,
- the ability to share the model (at low or no cost) with other interested parties, and,
- the ability to run the model in-house.

This last characteristic is important because the process of developing and calibrating a model is inherently an iterative process, with the modeler learning more about the problem as it is being modeled and tested. These iterations often can be carried out in a more timely and effective manner if carried out in-house.

Given these various goals, TACT made the decision to use the MARKet ALlocation

(MARKAL) model for ORD’s Air Quality Assessment (ECN, 2004). MARKAL is a bottom-up, linear, optimization-driven model that is non-proprietary, easily distributed, widely used, transparent, and that has an active user community. Although available MARKAL data at the onset of the project was not regionalized, did not extend to 2050, and did not include the emissions of criteria pollutants, the model itself is highly flexible and supports such modifications. Also, while the base version of MARKAL does not support elastic demands, MARKAL has been extended by various parties; a version called MARKAL-Elastic Demand and MARKAL-PE include elastic demands, and MARKAL-MACRO provides interaction with a macro-economic model of the economy.

2.2. Description of MARKAL

MARKAL was developed in the late 1970s at Brookhaven National Lab in response to the oil crisis. In 1978, the International Energy Agency adopted MARKAL and created the Energy Technology and Systems Analysis Program (ETSAP). ETSAP is a group of modelers and developers that meets every six months to discuss model developments, extensions, and applications. MARKAL therefore benefits from an unusually active and interactive group of users and developers, adding substantially to its credibility. MARKAL is currently in use by more than 40 countries for research and energy planning. In addition, the EIA recently adopted the MARKAL framework as the basis for its System for the Analysis of Global Energy Markets (SAGE) model. SAGE is used to produce EIA’s annual International Energy Outlook.

MARKAL is a data-driven, energy systems economic optimization model. The user inputs the structure of the energy system to be modeled, including resource supplies, energy conversion technologies, end use demands, and the technologies used to satisfy these demands. The user must also provide data to characterize each of the technologies and resources used, including fixed and variable costs, technology availability and performance, and pollutant emissions. MARKAL then uses straightforward linear programming techniques to calculate the least-cost way to satisfy the specified demands, subject to any constraints the user wishes to impose. Outputs of the model include a determination of the technological mix at intervals into the future, estimates of total system cost, energy demand (by type and quantity), estimates of criteria and greenhouse gas (GHG) emissions, and estimates of energy commodity prices.

The basis of the MARKAL model framework is a network diagram called a reference energy system, which depicts an energy system from resource to end-use demand (Figure 1). The RES divides an energy system up into four stages. The three technology stages represented in MARKAL are resource, transformation, and demand technologies. These technologies feed into a final stage consisting of end-use demands for useful energy services. End-use demands include items such as residential lighting, commercial space conditioning, and automobile miles traveled. Energy carriers interconnect the stages.

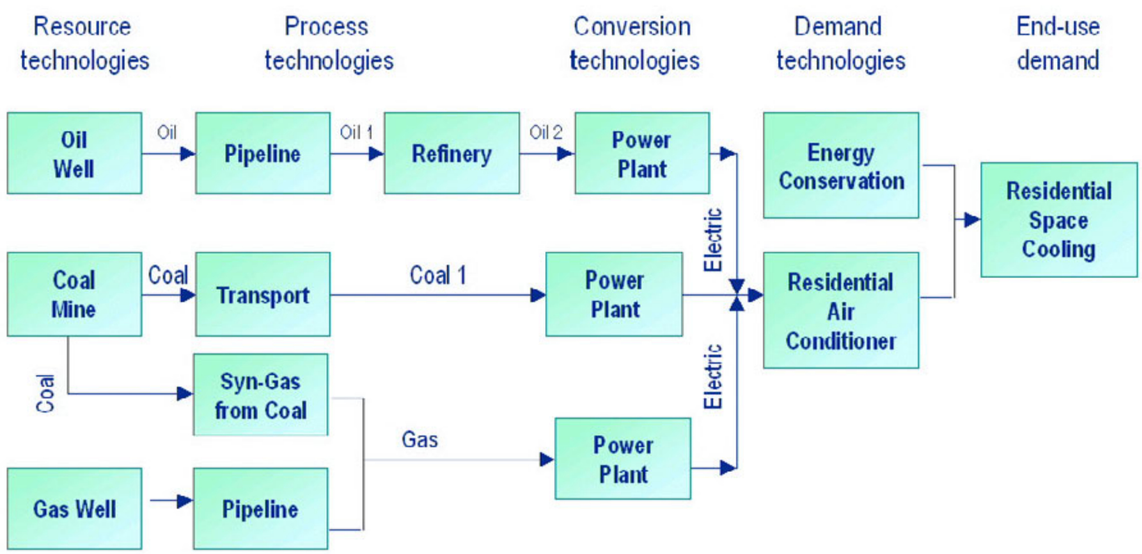

Figure 1. An Example of a Simple Reference Energy System.

The first technology stage, resource technologies, represents all flows of energy carriers into and out of the energy system. These include imports and exports, mining and extraction, and renewable energy flows. The second technology stage, transformation technologies, is subdivided into two classes: conversion technologies, which model electricity generation, and process technologies, which change the form, characteristics, or location of energy carriers. Process technologies include oil refineries, hydrogen production technologies, and pipelines. The final technology stage, demand technologies, are those devices that are used to directly satisfy the final RES stage, end-use service demands. Demand technologies include vehicles, furnaces, and electrical devices.

Energy carriers are the various forms of energy consumed and produced in the RES and can include coal variants (e.g., with different sulfur content), crude oil, refined petroleum products, electricity to different grids, and renewable energy (e.g., biomass, solar, geothermal, hydro). The model requires that the total amount of energy produced be at least as much as that consumed. The various technologies in a MARKAL model are inter-connected by energy carriers flowing out of one or more technologies and into others.

The MARKAL RES concept offers a significant enhancement over single sector energy technology models because it allows technologies and sectors to interact through the interconnections in the RES. For example, a technology that relies heavily on natural gas for fueling transportation technologies may shift the relative prices of fuels to the commercial, industrial, and residential sectors, potentially leading to a shift away from natural gas for some end uses. However, this means that even though TACT is currently only assessing technologies for transportation and electricity production, the RES database describing all significant end-use sectors, as well as all necessary upstream resource supplies and technologies, is needed.

2.3 Developing the EPA's U.S. MARKAL Model

The first objective in developing an EPA U.S. MARKAL model was to develop a database describing the RES. For the EPA U.S. MARKAL model, the database is being developed to describe technologies and end-use demand for the sectors of resource supply, transportation, commercial, residential, industrial, and electricity generation. For each technology represented in these sectors, the values for data parameters describing the technology's cost, technical performance, and availability are being obtained. A full listing of MARKAL data parameters appears in Appendix A. This section briefly describes the database development process. Further details appear in Appendix B.

The EPA U.S. MARKAL database is developed from a MARKAL database produced in 1997 by Brookhaven National Laboratory for the U.S. Department of Energy (DOE). All sectors have been thoroughly revised and updated, although the original values were maintained for several technologies that were outside this study's focus areas. Wherever possible, data for updating the RES database have been drawn from DOE's AEO 2002 and the input data to NEMS runs used to produce the AEO 2002.

AEO data were selected for the RES because it is a nationally recognized source of technology data and widely used where reference or default data are required. It presents mid-term forecasts of energy prices, supply, and demand. The projections are based on results from EIA's NEMS and are based on federal, state, and local laws and regulations in effect at the time of the model run. (U.S. EIA, Site 1) Where AEO data were not available in a form appropriate to the MARKAL RES needs, RES data were derived from other widely recognized authoritative sources. In every case, including the use of AEO data, the data source has been well documented with the original data source readily available to those of interest.

In the transportation sector, personal vehicle technology data were drawn from the DOE's Office of Transportation Technologies (OTT) Quality Metrics (QM) assessment. QM describes the analytical process used in estimating future energy, environmental, and economic benefits of DOE's Energy Efficiency and Renewable Energy (EE/RE) programs. QM has been an active annual DOE EE/RE-wide analysis and review procedure since 1993. (U.S. DOE, 2002) Section 3 presents a list of the personal vehicle technologies extracted from the QM report. Two additional vehicle technology characterizations were derived from a report titled Technical Options for Improving the Fuel Economy of U.S. Cars and Light Trucks 2010-2015 (DeCicco et al., 2001).

Data for the electricity sector were drawn from NEMS with supplemental data pulled from the Electric Power Research Institute (EPRI) Technical Assessment Guide (TAG). The TAG is a standard reference work for the energy industry that characterizes key electric generation technologies and their operation, costs, environmental impacts, etc.

At the time of this report, the representation of the industrial sector in the RES is still under development. Currently, the energy consumption from this sector is constrained to values derived from the AEO 2002 (future updates will incorporate AEO 2004 figures). Unlike other sectors, this sector is therefore presently unable to respond to changes in energy prices. Ongoing efforts to develop the industrial sector representation are centered on adapting the characterization used in EIA's SAGE model . This characterization describes six energy services within each of six industrial sectors. Additional documentation will be provided when this sector's development work is complete.

The database is divided into time periods of equal length of 5 years per period. The current database runs from 1995 to 2035. The eventual end-point of the database will be extended to 2055 in future work. Note that although results are needed in 2050, 2055 has been chosen as the end-year in order to eliminate possible end-effects for year 2050 which may occur in the model at the end-point year. Determining how to extend the database most appropriately out to the 2055 is an important step in the next phase of the project.

As each sector of the model is completed, data characterizing the associated technologies have been peer-reviewed for appropriateness of the data source, completeness of the technology options, and correctness of the methodology in converting the data from the original source to the MARKAL inputs. A separate document is under development that discusses the comments from the reviewers and the responses/actions resulting from these comments. That document will be a subsection of full database documentation provided to the future users of TACT MARKAL database. After assembling a complete representation of the energy system, the model was calibrated against the AEO 2002 report. This process is discussed in Appendix B. The goals of the calibration were to (i) ensure that the model was producing reasonable results, given its input assumptions, (ii) determine whether the model was providing a plausible, consistent representation of the key features of the U.S. energy system, (iii) identify why the differences exist in cases where our results differ from AEO results, and, (iv) identify any significant errors in the construction or characterization of the RES. It should be noted that an exact calibration of MARKAL to the AEO is not practical or desirable since the models are very different in structure and purpose. In addition, the AEO calibration underlies all scenarios, and therefore should not be construed as a reference case.

2.4 Using MARKAL to Develop Technological Scenarios

Scenarios are images of alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternative, internally consistent depiction of how the future may unfold, given assumptions about future economic, social, political, and technological developments as well as consumer preferences. A set of scenarios assists in the understanding of possible future developments of complex systems.

Scenarios explore plausible futures by using models to generate an outcome or set of alternative outcomes consistent with a set of motivating assumptions, sometimes called a storyline. This procedure allows the consequences of varying sets of plausible assumptions to be assessed. No attempt is made to calculate every possible future with this procedure, nor is there an attempt to assign likelihoods to alternative outcomes. Instead, the intent is to construct a set of scenarios that together cover the range of plausible futures. The process of developing, evaluating, and comparing a set of scenarios assists analysts and decision-makers in understanding the range of possible futures, how these possible futures are similar or different, and the drivers that may lead to each.

A scenario-based approach is particularly appropriate for assessments involving a long time horizon, such as assessments linked to global climate change. Technology developments are difficult to project over such horizons. Over a period of decades, it is not possible to predict which technologies will achieve fundamental breakthroughs and which will not. As a result, it is inappropriate to use the simple extrapolations that are conventionally applied in shorter-term energy futures analyses. In both the transportation and electricity generation sectors, several alternative potential technology trajectories that can be envisioned today diverge greatly from current standard technologies in very different ways. Changes in economic structures, consumer preferences, resource supplies, and other variables similarly lead to inherent unpredictability.

TACT plans to address the many uncertainties surrounding future technological development in the transportation and electricity generation sectors by using the scenario approach. Each scenario will be a MARKAL run satisfying an alternative, plausible set of assumptions and meeting the demands of the U.S. energy system across the model time horizon. Through the scenario assessment process, MARKAL will allow TACT to identify the specific changes in assumptions that cause the model to switch from one technology trajectory to another. Similarly, using techniques called modeling to generate alternatives (MGA) will allow evaluation of the range of potential outcomes for any given set of assumptions. This will provide some useful information about the range of possible results that can be expected. Together, these approaches will help develop and evaluate a set of scenarios that represents the range of possible technology futures.

Results from a selected set of these scenarios will serve as input to the ORD Air Quality Assessment. In addition, the scenario runs will be used to present discussions of the system-wide impacts of technology choices on emissions of criteria air pollutants through a variety of papers and reports.

TACT will also explore several alternative approaches for evaluating the effects of uncertainty on MARKAL outputs. One such approach will be to evaluate the MARKAL outputs for sensitivity information. Since MARKAL is a linear programming model, outputs called shadow prices and reduced costs are produced automatically. These provide valuable sensitivity information such as amount a constraint would need to be modified before the technological selections produced by MARKAL would change. The use of Monte Carlo simulation or similar techniques will also be explored to propagate uncertainties in MARKAL inputs through the model to obtain estimates of uncertainties in model predictions. Development of a plan for examining uncertainty will be one of the objectives in the next phase of this work.

2.5 Future Technologies for Scenario Analysis

To evaluate various technological pathways to 2050, future technologies for the transportation and energy production sectors are being added to the MARKAL database. Specific technologies in the transportation sector include FCVs, hybrid vehicles, biofuels, and hydrogen fuel. Specific technologies for the electricity production sector will be selected in FY’04. This report focuses on a subset of technologies for the personal vehicles sub-sector, including gasoline internal combustion engine (ICE) and hybrid vehicles, hydrogen FCVs, and associated hydrogen fuel infrastructures.

The literature is being reviewed to characterize these potential future technologies and determine the range of plausible future values for the key MARKAL parameters such as capital and operating costs and technology efficiencies. Section 3 describe the technologies considered in this report and the ranges of values discovered in the literature.

2.6 Emissions Consequences

An important capability of MARKAL is the ability to estimate the emissions that result from the various activities represented in the RES. MARKAL has the capability to estimate both the emissions of criteria pollutants as well as GHG emissions. The emissions factors used within MARKAL were recently updated, and these new factors have been used in the results presented later in this report.

Vehicle emissions depend on fuel, propulsion technology (e.g., ICE or fuel cell), emissions control devices, and vehicle age (cumulative miles traveled) through degradation of control equipment. Emissions from existing vehicles that make up the fleet at the model start year will also change over time due to the earlier retirement of older, more polluting vehicles.

Emissions factors for existing vehicles were calculated from actual 1995 light-duty vehicle fleet emissions based on the 1999 EPA National Air Quality and Emission Trends Report (U.S. EPA, 2000). Vehicle stock turnover and annual vehicle miles traveled (VMT) by vintage were calculated based on information from the Energy Information Administration (EIA 1998, 2003b) and the Transportation Energy Data Book, Edition 21 (Davis, 2001). Degradation estimates were based on a variety of sources depending on the pollutant, including the EPA Federal Test Procedure, EPA’s Mobile 6 model (U.S. EPA, 1999), and the American Council for an Energy Efficient Economy (ACEEE) Green Book methodology (DeCicco, J. and Kliesch, J., 2001).

For new ICE and hybrid vehicles, emissions factors were based on standards specifications for Tier 1, low emission vehicles (LEV), ultra low emission vehicles (ULEV), super ultra-low emissions vehicle (SULEV), and Tier 2 compliant vehicles (U.S. EPA, 2000a). For Tier 2 compliant vehicles, emissions factors were derived from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, developed by the Argonne National Laboratory (ANL,2001). All hybrid vehicles were assumed to be SULEV compliant. For all other ICE vehicles, a mix of compliance levels was assumed based on national and state regulations. Degradation estimates were based on the Mobile 6 model, EPA's Tier 2/Sulfur analysis (U.S. EPA, 2000), and the ACEEE Green Book methodology.

In addition to providing emissions estimates, including emissions factors also facilitates investigations such as the determination of technological scenarios that most cost-effectively meet emissions reduction targets, maximize emissions reduction, or allow emissions trading between sectors.

The next two sections provide details about alternative automobile technologies, such as advanced ICEs, hybrids, and hydrogen fuel cells and technologies for implementing a hydrogen infrastructure. These sections provide a template for how additional vehicle and energy technologies will be incorporated into MARKAL. A variety of scenarios have been developed and evaluated involving these technologies.

Section 3
Transportation Technologies

This section describes the transportation technologies considered in TACT's scenario analysis. Following a brief description of the vehicles in the RES database, the technologies highlighted in the scenario analysis are described in detail. These include hybrid gasoline electric vehicles, FCVs, and hydrogen fueling infrastructures. A description of each of the technologies is given, followed by consideration of issues that may affect adoption of the technologies and the potential emissions implications of technology adoption.

Table 3 is a list of the technology types available as personal vehicles in the EPA MARKAL RES database. For future technologies, the first year of their availability is also shown. Most of these technologies are derived from OTT's Quality Metrics report. Two additional technologies, representing conventional internal combustion engine vehicles with "packages" of efficiency improving technologies, are taken from DeCicco et al. (2001). The existing gasoline and diesel fleet phases out linearly over 15 years and is unavailable to fill new demand. MARKAL chooses a least cost mix of new technologies to fill demand as existing vehicles retire, dependent on the scenario input assumptions.

Table 3 Personal Vehicle Technologies.

Technology	Description	Year Available
Existing gasilone	Existing auto fleet	In place
Existing diesel	Existing fleet (light trucks only)	In place
Conventional	Gasoline powered	2000
Moderate MPG[a]	8–16 mpg more than Conventional[b]	2010
Advanced MPG	14–23 mpg more than Conventional[b]	2010
Advanced diesel	8–12 mpg more than Conventional[c]	2005
Electric	Electric powered	2005
2X hybrid	100% mpg increase over Conventional	2005
3X hybrid	200% mpg increase over Conventional	2015
flex ethanol	Fuel is E85 (gasoline/ethanol) or gasoline	2005
Gasoline fuel cell	FCV powered from gasoline reformer	2010
Fuel cell	FCV powered directly with hydrogen	2020

[a] MPG = miles per gallon.
[b] Increase varies with car class. Lower end of the range is for pick-up trucks.
[c] Advanced diesel is available for all classes. Lower end of the range is for pick-up trucks.

Five classes of personal vehicles are represented: compacts, full-size, minivans, pick-up trucks, and sports utility vehicles (SUVs). Market shares for these classes in the RES database are fixed at their 2000 sales share levels: 25, 27, 7, 20, and 21 percent, respectively. The lifetime for all vehicles is set to 15 years. Average VMT per year per vehicle are fixed at their 1995 values of 11,203 for cars and 12,018 for trucks and SUVs. All data from Transportation Energy Data Book, Edition 21 (Davis, 2001). Average VMT per year values are used to convert vehicle fixed (capital and operating) costs into MARKAL units of dollars per billion VMT per year capacity. Allowing these values to increase over time would tend to shift model solutions towards more efficient vehicles, as variable costs of operation would be increased relative to fixed costs.

3.1 Hybrid Vehicles

Because of their low additional capital costs, ability to make use of the existing gasoline fueling infrastructure, and improved efficiency over conventional vehicles, hybrid technologies are expected to compete for market share in the future. Thus, the representation of hybrid vehicles in MARKAL is critical. Hybrid technologies and the approach for those technologies into MARKAL are discussed in this section.

3.1.1 Description of the Technology

Electric vehicles have long been touted as a way to minimize highway pollution, but their acceptance has been limited by performance issues and limited range. Recent improvements in electric motors and electronic controls have helped the performance issue, and battery improvements have helped the range issue. Nonetheless, the weight of batteries with sufficient storage to allow an acceptable range between charges reduces the vehicle's performance and efficiency.

Hybrid vehicles, sometimes called hybrid electric vehicles, or HEVs, are a blend of the technology provided by ICE and electric motors. The range issue is eliminated by using an efficient ICE to keep the batteries charged. Regenerative braking systems complement the engine's capacity to recharge the batteries by recovering the energy normally lost as heat.

Generally, the ICE component of HEVs is a much smaller engine than would be needed to produce all of the energy needed to power the vehicle. It is used mainly to keep the batteries charged. The electric motors associated with the batteries produce the torque needed for better performance than would be realized by the small engine. Further, since the engine is not the sole source of power for the vehicle, it can be operated at conditions more amenable to efficiency and lower pollution (e.g., optimal revolutions per minute).

Figure 2 illustrates a typical HEV showing the primary components: internal combustion engine (1), transmission (2), electric motor (3), electronics (4), fuel tank (5), and batteries (6).

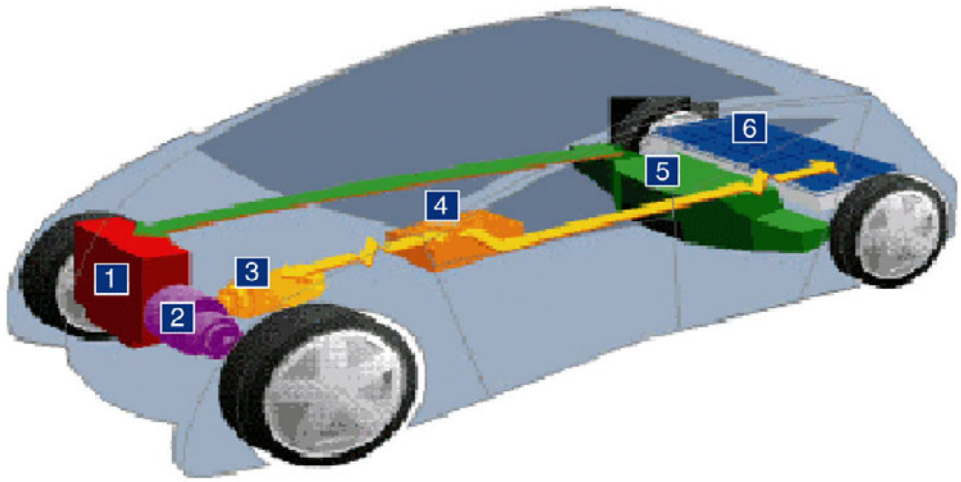

Figure 2. Typical Hybrid Vehicle Configuration.

3.1.2 Design Considerations

There are three major design considerations common to all HEVs:

- Propulsion system configuration (series or parallel),
- Power unit (combustion engine), and
- Energy storage system.

Propulsion system—The combustion engine and electric motors of HEVs can be configured in either series or parallel. In a series configuration, an electric motor is the only means of driving the wheels. The electric motor gets its power either directly from the battery pack or from a generator powered by an engine in much the same way as a portable generator. Electronic controls determine how power to the motor is shared between the battery and the engine/generator set. Since there is a direct connection of the motor to the wheels, there is no need for a complicated transmission and clutching system, thereby reducing weight. It also allows the engine to operate at optimal conditions since it is used only to keep the batteries charged. It also allows the use of non-conventional engine types such as turbines, Stirling engines, or any other means of driving the generator. A disadvantage of the series configuration is cost. Today's ICEs are relatively inexpensive per unit of power compared to the modern batteries, generator, and electric motors used in HEVs. Battery packs must be larger in the series configuration.

Series hybrids show their greatest advantages under relatively slow, stop-and-go driving conditions. Here, the advantage of the high torque at low speeds outweighs the need for efficiency at cruising speeds. Because of this, the series hybrids currently under development are primarily for busses and other heavy duty urban vehicles.

In parallel HEVs, both the engine and the motor can drive the wheels. This ability to switch adds complexity to the HEV by requiring a transmission and generally a clutching system. The engine in parallel HEVs is larger than in the series configuration since it does a greater portion of powering the vehicle, but the battery packs are smaller. Since engines are currently less expensive than batteries and motors, these tradeoffs are cost-effective. This cost advantage will diminish as battery and motor costs come down over time. The automobile shown in Figure 2 is a parallel HEV.

The parallel configuration is also more suited to highway driving. Both the Honda Insight and the Honda Civic Hybrid are parallel HEVs.

Though series and parallel are the two general classifications of HEV configuration, there are several modifications of the two designs. One is the "split" drive train where the engine drives one set of wheels and the electric motor drives the other. Using this configuration the vehicle can operate in 4-wheel drive mode or can switch from engine to motor as conditions warrant.

The Toyota Prius uses a "series/parallel" drivetrain. With this configuration, the vehicle operates in either series or parallel mode depending on driving conditions. This requires a coupling of the two systems using a "power split device" and computerization to determine the series/parallel choice. This configuration incorporates some of the best of both series/parallel configurations, but at a cost. It has the higher cost of the series configuration because of the larger battery pack and the need for a generator, and has the added complexity of the parallel configuration. It also requires more computing power and electronic controls.

Power unit (combustion engine)—Conventional spark ignition engines are used almost exclusively in today's HEVs. However, compression ignition direct injection (CIDI) or "diesel" type engines can be used just as well and would add additional efficiency to the HEV package. If the HEV has a series configuration, practically any type of engine can be used, including gas turbines, Stirling engines, Atkinson engines, fuel cells, etc. The ability to use non-conventional engine types introduces the potential for non-conventional fuels (e.g., biomass-derived fuels). Concerns, however, have been expressed about whether CIDI engines will be able to meet planned EPA emission regulations (Ball, 2003).

<u>Energy storage system</u>—Battery packs are used exclusively to store energy in today's HEVs. These can add considerable weight to the vehicle with a consequent reduction of efficiency. The primary considerations for batteries are (DOE, 2003a)

- High specific energy (weight-to-energy ratio),
- High peak and pulse-specific power,
- High charge acceptance (for regenerative braking systems),
- Long calendar and cycle life,
- Recycleability, and
- Abuse tolerance (safety).

The most common automotive battery today is the lead-acid storage battery found in practically all cars. This design is sufficient for the normal electrical needs of the conventional automobile. There also is a well-established infrastructure for manufacture and recycling. However, lead-acid storage batteries are heavy (low specific energy), have poor low temperature performance, and relatively short calendar and cycle life. Also, the strong sulfuric acid integral to this technology presents safety concerns in the event of car crashes. Because of these disadvantages, alternate battery designs have been pursued for HEVs.

The HEVs currently on the road in the largest numbers, Toyota Prius and Honda Civic and Insight, use sealed Nickel-Metal Hydride (NiMH) modules. The NiMH battery pack is designed to be recharged tens of thousands of times and provides potentially significant safety advantages because the ingredients are sealed in a carbon composite case and are essentially inert, nonflammable, and noncaustic. Disadvantages of NiMH batteries include high cost, high self-discharge, and low individual cell efficiency. Other battery technologies such as lithium ion, lithium polymer, and nickel cadmium also have potential for HEVs but will require additional development to bring down cost and to mitigate other disadvantages of the technologies.

Other interesting potential technologies for energy storage systems are ultracapacitors and flywheels. Ultracapacitors have a higher specific energy than batteries and can deliver strong pulses of power. They may find an application in recovery of braking energy and for power assist during passing or hill climbing. Flywheels have the potential to store kinetic energy (e.g., from braking), are free of hazardous materials, and are not affected by temperature extremes. However, flywheels have a low energy density. More research will be needed to integrate these technologies into mainstream HEVs (DOE, 2003b).

3.1.3 Issues for Implementation

Several issues affect the potential for HEV adoption. These include cost and performance, consumer acceptance, fuel infrastructure, and fuel diversity and security.

Cost and performance—The initial cost of an HEV may be a deterrent to penetration of the technology. However, the cost penalty is expected to decrease with time as the component technology improves and as experience with manufacturing and operation continues to grow. Figure 3 shows estimates from various sources of HEV cost versus conventional vehicles for the years 2005–2035. The high estimate of 36 percent is from one source that assumes the cost of early retirement of unamortized equipment, tooling, and engineering in 2010 (Sierra, 1999).

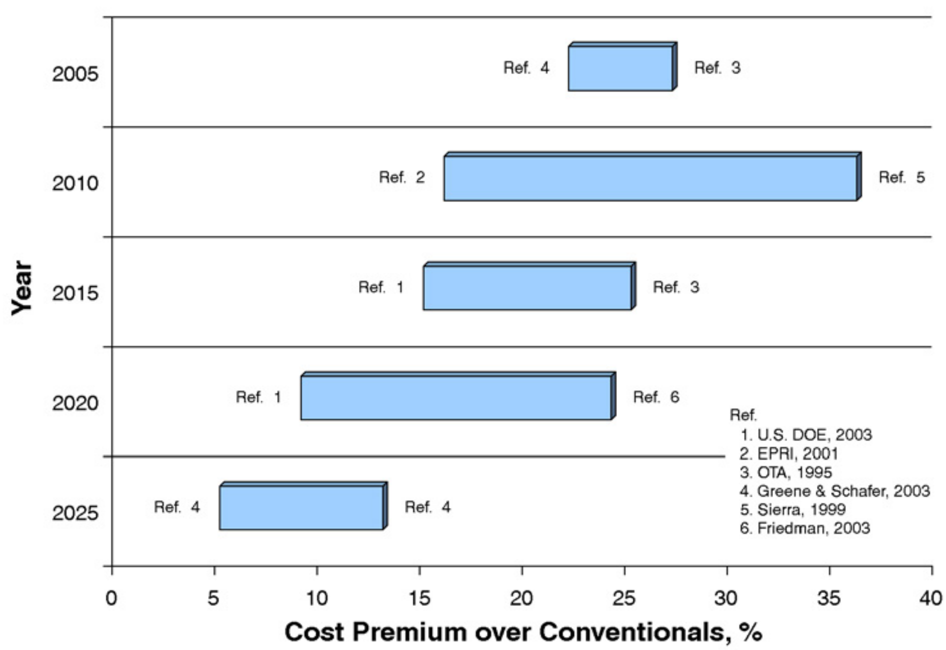

Figure 3. Range of Cost Premiums for HEVs.

Increased fuel economy over conventional vehicles will partially offset the higher initial cost of the vehicles. Figure 4 shows a comparison of fuel efficiency ranges reported for full size HEVs and the expected improvements. Fuel economy reported in Figure 4 came from the Research Triangle Institute (RTI, 2002). The RTI data represent a compilation of data from various published sources.

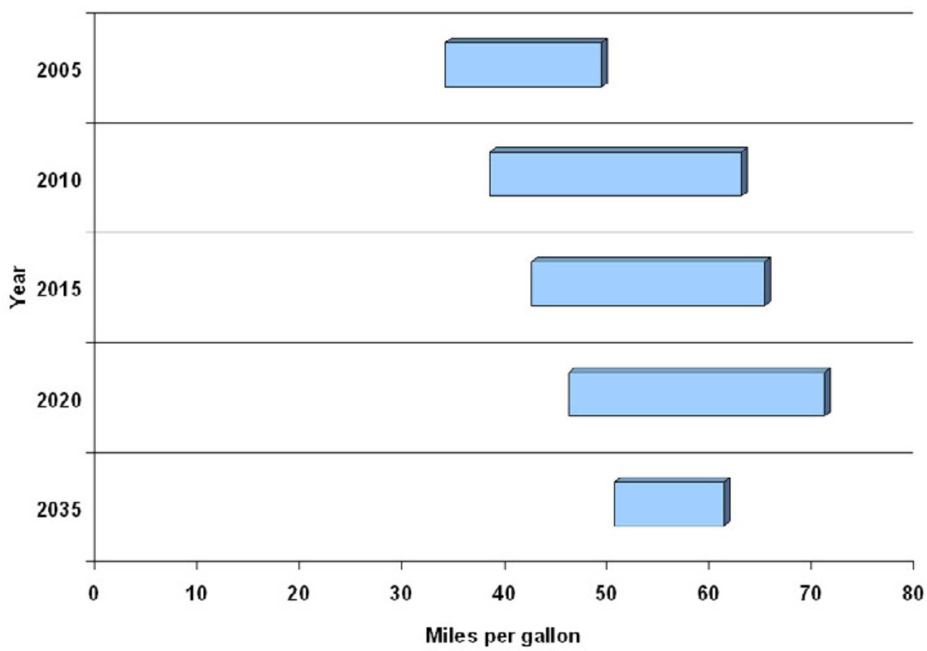

Figure 4. Range of Fuel Economies for HEVs.

Consumer acceptance—An issue affecting the adoption of all new vehicle technologies is the degree to which consumers will accept the new technology. Because HEVs refuel in the same way as conventional vehicles and use existing fuels (gasoline or diesel) and the existing fueling infrastructure, HEVs are expected to require little or no change in consumer behavior. This factor will tend to ease consumer acceptance relative to other new vehicle technologies.

J. D. Power and Associates estimates that hybrid sales will climb to 500,000 shortly after mid-decade when five automakers are selling them. In a survey of 5,200 new car buyers, Power found that 60% would “definitely” or “strongly” consider buying a hybrid (JDPA, 2002).

Fuel infrastructure—The fact that HEVs utilize existing fuels and fuel infrastructures also avoids the need for expensive investments in fueling infrastructures, an important consideration for hydrogen fuel cell vehicles.

Fuel diversity and security—Today's HEVs do not provide the option of using electricity from the grid to recharge the batteries. However, the technology for switching to a plug-in variety of HEVs exists and could be implemented. This could be an "add-on" option by leaving space for additional battery capacity and wiring harnesses for the additional controls. The plug-in option would allow these vehicles to take advantage of the fuel diversity in the electricity generation sector, providing fuel security and reduced dependence on imported petroleum. Consumers would also be able to respond to fluctuations in gasoline and electricity prices.

In a study of consumer preferences, EPRI found that the majority of participants preferred charging the vehicle on their own premises until the costs and benefits were explained. Then, the preference for "plugging in" varied with price and other key attributes. The EPRI study further showed that 35% to 46% of the respondents who drive a mid-sized vehicle would choose an HEV over a conventional vehicle and that the market potential is sensitive to price (EPRI, 2001, p. xxiii). The EPRI study noted that tax credits and other incentives could offset much of a consumer's purchase and life cycle costs of HEVs (EPRI, 2001, p.2-21).

A related convenience brought about by the marriage of electricity to conventional fuel in HEVs is that power can be supplied as well as consumed by the vehicle. At least one existing HEV (Toyota Estima) supplies household current through conventional outlets (Toyota, 2003). This option would allow HEVs to serve as generators for emergency and off-grid power (e.g., for campers), though supplying power directly to the electric grid is a longer-term possibility. This option may increase perceived value and consumer acceptance of such vehicles.

3.1.4 Emissions considerations

The ICE that is an integral part of the HEV can be designed to be less polluting than conventional ICEs due to several factors. First, the HEV ICE can operate at an optimal revolutions per minute. Though designs vary, HEVs can use the electric motors for the high-torque demands of overcoming the inertia of a vehicle at rest. If the ICE is connected to the drive train, then it can be used in the cruising range of the vehicle where it is more efficient. Second, the smaller, lighter ICE heats up quickly. This reduces start-up emissions, which is a primary challenge in reducing tailpipe emissions (EPRI, 2001, p. 3-32). In addition to these benefits, the ICE used by HEVs is smaller, so there is less weight and, consequently, less fuel must be used to move the vehicle. Finally, most HEVs use regenerative braking, another fuel-saving measure. In general, improved fuel efficiency will lead to lower emissions.

A detailed modeling of emissions from HEVs is a complex task since emissions will depend on the degree to which the ICE or the electric motor is powering the vehicle throughout the drive cycle. Hence, emissions will be sensitive to the design of each HEV. For the purposes of this scenario analysis, which considers the potential emissions consequences of varying scenarios, HEVs have been modeled as SULEV vehicles. (All of the hybrid vehicles currently on the U.S. market are certified SULEV.) TACT's emissions modeling for the ORD Air Quality Assessment will consider the factors affecting HEV emissions in more detail.

3.2 Fuel Cell Vehicles

Fuel cells are another technology that is expected to compete for market share in the future. There are still many challenges in reducing costs and optimizing design, and it is expected that fuel cell vehicles will not compete for market share until at least 2015–2020, though with unanticipated cost and performance breakthroughs this date could be earlier. This section characterizes fuel cell vehicles and these challenges.

3.2.1 Description of technology

Different fuel cell technologies are being developed for many applications. Fuel cell designs range from small proton exchange membrane (PEM) fuel cells that power vehicles to large stationary power plants using molten carbonate or solid oxide fuel cells. A thorough description of the various types of fuel cells and their operational principles can be found elsewhere (U.S. DOE, 1994).

Although the types and designs are different, all fuel cells are electrochemical devices that convert the chemical energy in H_2 into electricity, heat, and water vapor without combustion. A fuel cell consists of an anode and a cathode separated by an electrolyte, which is a fluorinated Teflon-based material in the case of a PEM fuel cell.

Figure 5 shows the principle of operation of a H_2/air fuel cell. The fuel (H_2) and oxidant (air) gases flow past the anode and cathode, respectively. A platinum catalyst on the anode encourages H_2 to become H_2 ions by releasing electrons, which pass through an external circuit to provide electricity. The circuit is completed by the transport of the ions by the ion-conducting electrolyte to the cathode where they are oxidized to water. These individual cells are electrically connected in series to form a stack with the desired voltage/current output. If the fuel cells are operated using fossil-based fuels, then a fuel reformer is required to reform the fuel into a H_2-rich mixture for use by the stack.

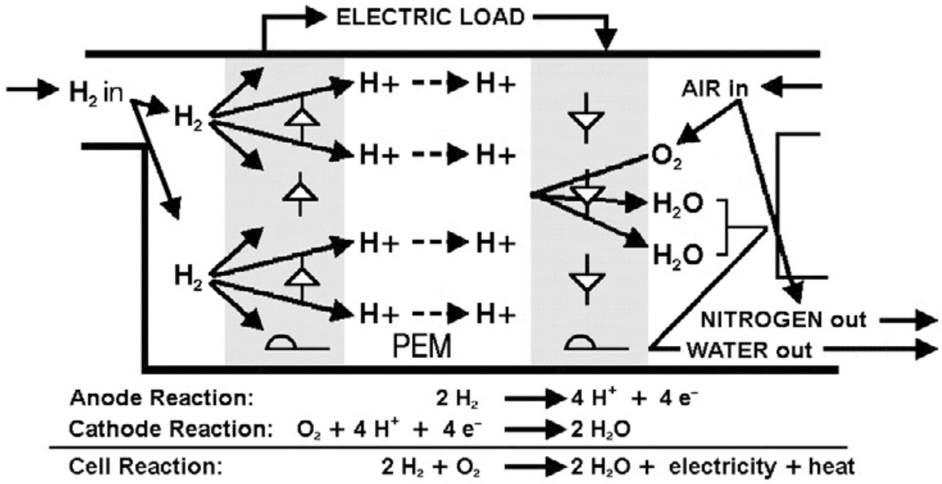

Figure 5. PEM Fuel Cell Operation.

The PEM fuel cell presently is the leading contender to provide power for FCVs. Its primary advantages include a low operating temperature (~80 ºC), high current densities, a fast start capability, no corrosive fluid spillage hazard, low weight, small size, and a potentially low cost to manufacture.

<u>3.2.2 Fuel Cell Engine Subsystems</u>

Figure 6 illustrates the basic functional subsystems of a FCV. Like the familiar internal combustion engine, the fuel cell engine combines fuel and air to create power. Fuel is stored in an external tank that can be refilled, providing the vehicle with the required range. Unlike an internal combustion engine, however, the fuel cell engine converts the chemical energy in the fuel (H_2) directly into electricity without combustion, as described above. Since no combustion is involved, there are no emissions other than water vapor. H_2-powered FCVs are therefore categorized as zero-emission vehicles. The electricity produced by the fuel cell engine is supplied to the electric motor that power both the vehicle's drive wheels and auxiliary equipment.

If the FCV is powered by a fossil-based fuel such as methanol or gasoline, an onboard fuel processor is required to reform the fuel into a H_2-rich mixture for use by the fuel cell. Because external combustion may be required to increase the gas temperature for the reform process, realtively small emissions of CO and NO_X result. Thus, a FCV with a reformer is considered a near-zero-emission vehicle.

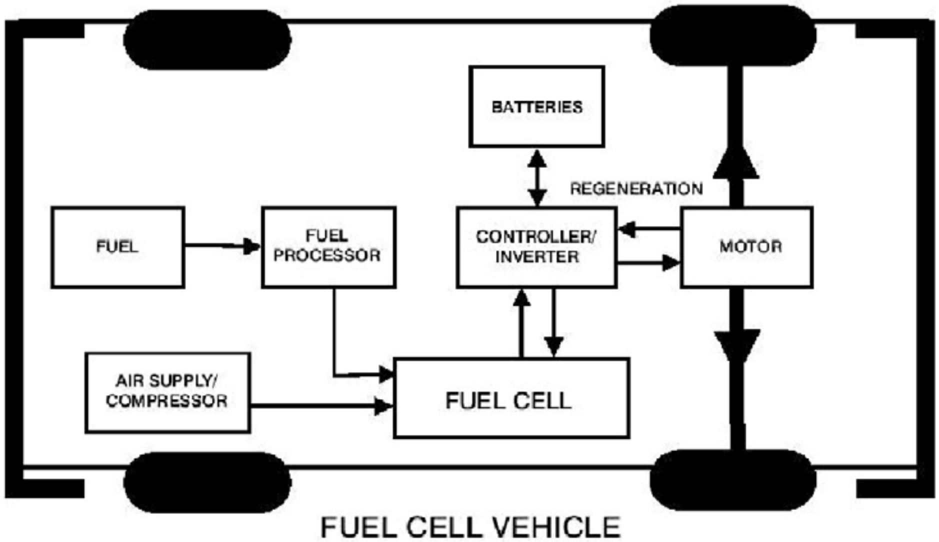

Figure 6. Fuel Cell Vehicle with Fuel Processor.

As shown in Figure 6, a number of subsystems are required to make the fuel cell engine operate. These various subsystems include the fuel cell array, air delivery, fuel delivery, cooling system, electrical system, control system, and electric traction drive. These are discussed briefly below.

Fuel cell array—The fuel cell array is the heart of the fuel cell engine. It is composed of a number of PEM fuel cell stacks arranged to provide the required power at the desired voltage and amperage. Internal manifolds direct the flow of fuel, air, and coolant through the array.

Air delivery system—The air delivery system is one of the most critical subsystems. It provides air to the fuel cell array at a flow and pressure corresponding to power demand. As more power is demanded from the fuel cell array, higher pressure and flow must be provided to generate power. The air delivery system can either be a pressurized design or a design that operates at ambient pressure. In the pressurized case, the fuel cell engine is designed to provide maximum power at a pressure in the vicinity of 30 pounds per square inch gauge (psig). Air from the outside is drawn in through a filter by an electrically driven compressor and increased to full operating pressure by a turbocompressor. The turbocompressor is powered by energy recovered from the exhaust air from the engine. Air flow through the engine is also used to remove the water that is produced by the electrochemical reaction.

An ambient pressure fuel cell engine is also being developed. At near-atmospheric pressure, only a blower and its drive motor are required. Although ambient pressure operation eliminates the need for a compressor, turbocompressor, and related equipment, the size of the fuel cell array and related manifolds are larger. The efficiency gain made possible by the higher performance of pressurized stacks tends to be offset by the parasitic power requirement of the compressor. Thus the cost and efficiency trade-offs between pressurized and ambient air delivery are difficult to quantify.

Fuel delivery system—For an H_2 FCV, fuel may be stored as high-pressure compressed H_2 gas that is stored in lightweight composite cylinders or as a cryogenic liquid. Metal hydride and carbon nanotube storage systems are also under research and development. If the fuel is methanol or gasoline, a fuel processor or reformer must be included in the fuel delivery system. A reformer can efficiently deliver H_2 to the fuel cell array by splitting the hydrocarbon molecule. A reformer produces trace emissions (CO and NO_X) as it burns some of the hydrocarbon to provide the necessary heat of reaction. The reformer also adds cost, weight, and complexity to the overall engine system.

Electrical system—The electrical system provides the power interface between the fuel cell array and the electrical equipment for the engine and vehicle. An inverter is required to convert the direct current (DC) power produced by the fuel cell stack into alternating current (AC) power for use by an induction motor. Although a DC motor could be utilized and the inverter eliminated, an AC induction motor is usually the motor of choice because its small size, ruggedness, reliability, and cost advantages.

Other subsystems include the cooling system to maintain the fuel cell operating temperature and the control system to coordinate operation of all other systems.

3.2.3 Hybridization

As with internal combustion engines, it is possible to add batteries for additional storage capability to form a fuel cell hybrid vehicle (FCHV). The FCHV subsystems would be the same as those in a FCV (see Figure 6) but with more batteries and a more sophisticated control system. Some advantages of a hybrid configuration might include:

- regenerative braking to recover the kinetic energy normally dissipated as heat during braking,

- power during cold start to eliminate the need for near-instant start up of the fuel processor for gasoline- or methanol- powered fuel cell engines, and
- additional batteries as a power boost for acceleration and hill climbing, thereby allowing a smaller and less expensive fuel cell engine.

FCHVs will be considered in TACT future analyses.

3.2.4 Fuels and Processors

The three types of FCVs being developed are a direct H_2 FCV, an alcohol (methanol) design, and a gasoline version. In a direct H_2 FCV, the H_2 can be stored on-board as a high pressure gas or in the form of a metal hydride. Weight, storage density, and charge/discharge cycles issues have not been totally resolved for metal hydrides, however. Therefore, cost estimates in this report are based on the high pressure tank option. This subsection describes onboard reforming of methanol and gasoline to H_2. Building a large-scale H_2 infrastructure—consisting of production, storage, transmission, distribution, and delivery—are discussed in Section 3.3.

Methanol is a good H_2 carrier for on-board reforming because it is a liquid at room temperature and ambient pressure. Even though methanol has some properties different from gasoline (e.g., methanol is hygroscopic and corrosive), it could be handled in much the same manner as gasoline. As a result, the development of a methanol fueling infrastructure may be significantly cheaper than for H_2. Since methanol is a very simple molecule (a single carbon atom linked to three hydrogen atoms and one oxygen-hydrogen bond), releasing the H_2 is easier to accomplish than with other liquid fuels such as gasoline.

In addition to methanol reformer FCVs, there is current effort to develop a direct methanol fuel cell. No reformer is needed in this case, as the methanol is injected directly to the fuel cell's anode, where it is oxidized to CO_2, releasing H_2 ions and electrons. This technology is not considered in the current scenario analysis, but will be considered in future analyses.

Gasoline can also be used as a H_2 source, but it is more difficult to reform than methanol. Additionally, very low sulfur gasoline with low aromatics is required so that reformer and fuel cell stack catalysts are not contaminated. If very low sulfur fuel is not available, onboard desulfurizer units must be used reduce fuel sulfur to the approximately 30 parts per billion by volume level necessary for high reformer performance and fuel cell stack endurance.

Figure 7 presents a fuel processor flow diagram. On-board processing (reforming) of H_2-rich fuels can be accomplished by essentially three techniques: steam reforming, partial oxidation (POX), and auto-thermal.

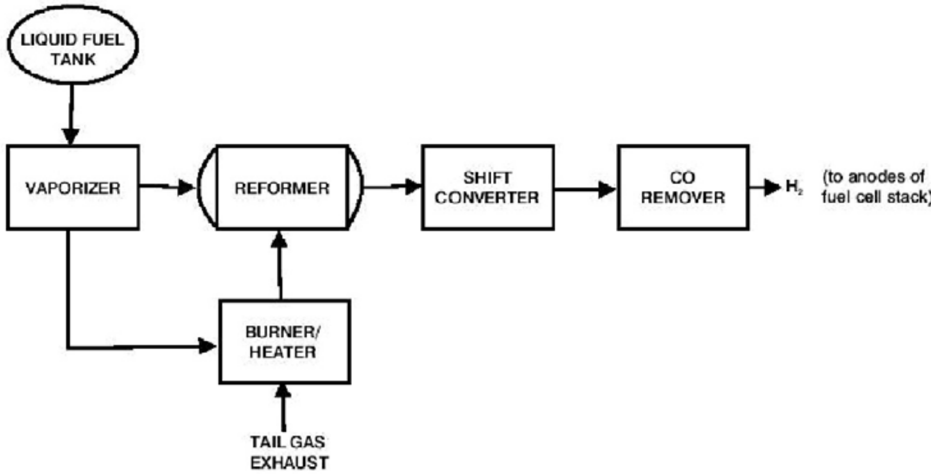

Figure 7. Fuel Reformer Flow Diagram.

Steam Reformers—Steam reforming combines fuel with steam over a catalyst, producing H_2 and CO. This technology yields a very high concentration of H_2, but a shift converter can also be added to further increase the concentration by converting the CO to more H_2 and CO_2. Generally, this endothermic reaction must be powered by burning some of the fuel to maintain the proper reformer temperature, and generating the heat required to power the reaction can result in long start-up times. After start-up, the heat can be supplemented by hot exhaust from the fuel cell's cathode. Some of the required heat can be supplied also by burning the anode exhaust gas (only about 85% of the H_2 produced is utilized by the fuel cell stack). Only simple hydrocarbons such as methanol or ethanol can be processed by steam reforming. Thus, this approach does not offer full fuel flexibility. Additionally, the reformer catalyst is extremely susceptible to poisoning from contaminates such as sulfur. It does, however, offer the potential for the lowest cost and smallest size. Methanol-based steam reformers have been demonstrated on-board in FCVs.

POX reformers—POX systems operate at much higher temperatures than steam reforming. They have the advantage that operation is possible with a variety of fuels such as gasoline, methanol, or ethanol. The process combines fuel with O_2 to produce H_2 and CO via an exothermic reaction. As with steam reformers, POX reformers use subsequent water-gas shift converters to convert the CO to more H_2 and CO_2. The reaction can provide a very fast response to transients, but additional equipment may be required to remove excess heat. Typically, prototype POX reformers only require a few seconds to "light-off" and begin the reaction. No POX reformers have been demonstrated in on-board FCVs.

Autothermal reformers—Autothermal reforming combines fuel with steam and air and is a mixture of the POX and steam reforming processes. It combines the reactions of steam reforming and POX such that the exothermic heat from the POX provides the heat for the steaming reforming process to proceed. This allows for a lower operating temperature of the reformer. This procedure produces a more concentrated H_2 gas stream than POX but less concentrated than the steam reforming process. The reformer is fuel flexible.

3.2.5 Issues for Implementation

Issues affecting the implementation of FCVs include the cost and performance of fuel cell engines, the expense and logistics associated with developing a hydrogen infrastructure, the availability and price of natural gas, and the availability of platinum.

Cost and performance—A principal challenge facing PEM fuel cell engine developers is to reduce costs. Although several subsystems are involved in a fuel cell engine as outlined above, the fuel cell stack is the major cost component associated with the engine. Three major challenges in reducing the cost of the stack are reducing the cost of the electrode plates, reducing the amount of platinum on the electrodes, and developing a cheaper but effective electrolyte membrane. To date, the cost of producing an entire fuel cell engine (stack, fuel processor, on-board clean-up, controls, etc.) is projected to be about $300/kW at mass production and based on current technology. However, achieving the cost production target of competitiveness with internal combustion engines (around $50/kW) will probably require additional technical innovation to find pathways for significant cost reduction.

Several cost analyses (e.g., ADL, 2000) have been conducted of the mass production capital cost estimates for the FCV drive train. These studies indicate that the drive train of a H_2-powered FCV will cost around $2000 more than a conventional vehicle. Another $200 to $900 can be added to that total for methanol- and gasoline-powered FCVs as a result of the onboard reformer and related equipment. Depending on the FCV type (small car, large car, minivan, sport utility vehicle, or van/pickup truck), the estimated capital cost ratio (capital cost for a FCV divided by the capital cost for a conventional vehicle in the same year) ranges between 1.15 and 1.4. When FCV vehicles are introduced, the cost ratio is expected to be at the upper end of this range, diminishing to the lower end as the technology matures.

Figure 8 shows ranges of reported estimates of FCV capital costs, normalized to similar parameter values for a conventional vehicle. Figure 9 contains ranges for fuel economy. For the capital cost values, the high end of the ranges refer to when the FCVs are initially introduced, while the low end of the ranges represent the cost of more mature FCVs after several years of commercial production. The high end of the ranges for fuel economies, however, are for mature FCVs, with the lower ranges the initial values. Sections 5 and 6 discuss scenarios examining the effects of variation in FCV cost and performance.

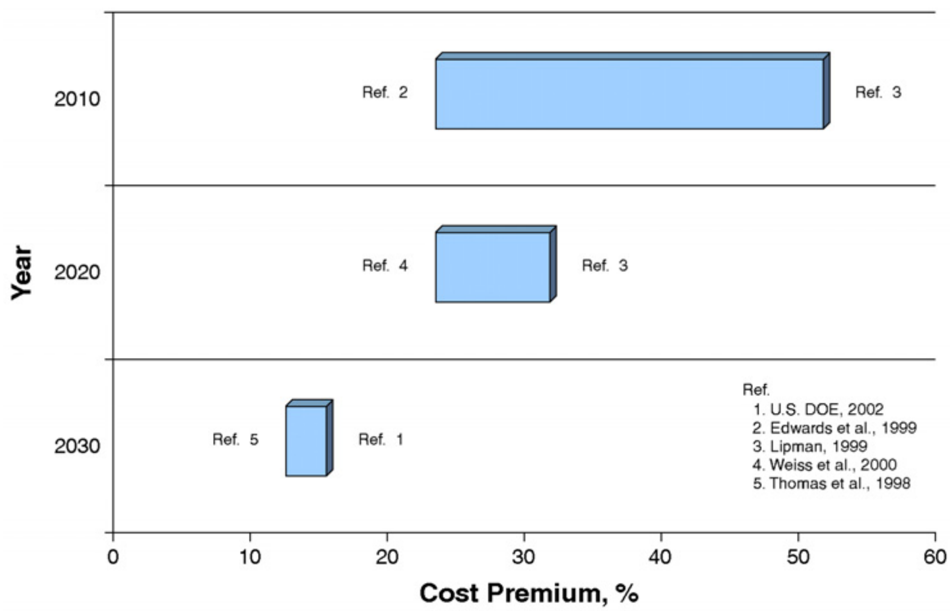

Figure 8. Ranges of Cost Premiums for Fuel Cell Vehicles.

Hydrogen infrastructure—For large-scale penetration of direct H_2 FCVs, a H_2 infrastructure consisting of production, storage, transmission, distribution, and delivery would be required. Development of such an infrastructure could be extremely costly. These issues are considered further in Section 3.3 and Section 4.

Natural gas availability and price—Natural gas is the most frequently proposed feedstock for producing methanol for FCVs (although alternate pathways will be considered in TACT's upcoming biofuels scenario analysis). The process for conversting natural gas to methanol is well known, and methanol converters are commercially available. However,

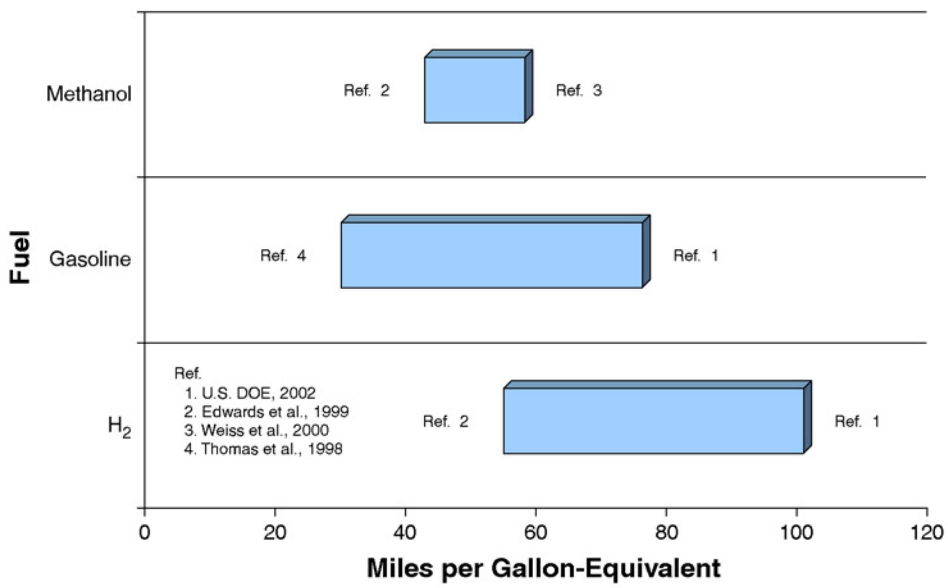

Figure 9. Ranges of Fuel Economy for Fuel Cell Vehicles.

using natural gas as a feedstock would make the methanol production cost extremely dependent on the cost of natural gas, which is expected to be quite unpredictable over a typical 30-year planning cycle. In addition, the natural gas share of electricity generation is widely predicted to increase substantially over the coming two decades (Hester, 2000; EIA, 2003a). MARKAL's RES enables the modeler to examine the potential consequences of these competing demands for natural gas. These issues will be considered in TACT's scenario analyses for methanol FCVs.

<u>Platinum availability</u>—Another issue that has been raised regarding FCVs is the amount of platinum required for FCV catalysts. Borgwardt (2000) is pessimistic relative to the issue of whether platinum supply can meet demand when large numbers of FCVs enter the market.

3.2.6 Emissions considerations

For each type of FCV, well-to-wheels emissions of VOCs, CO, NO_X, and CO_2 can be estimated (Weiss et al.. 2000). This section considers the impact of FCV designs on vehicle emissions. TACT's MARKAL analyses will examine full well-to-wheels emissions. For vehicle emissions, FCVs provide the opportunity for significant emissions reductions over internal combustion engine and hybrid designs because combustion is essentially eliminated, although a small amount of combustion occurs for steam reformers. Additionally, the catalytic-based reformer processes require local cleanup of certain contaminants, (e.g., CO). The H_2-powered FCV would be a true zero emission vehicle because only water vapor is emitted as a result of the electrochemical reaction inside the fuel cell stack. Alcohol- and gasoline-powered FCVs are not zero emission vehicles. Both vehicle types produce small combustion emissions of CO and NO_X, and evaporative VOC emissions are negligible. However, these emissions are expected to be well below the most stringent proposed emissions specifications, including California's near zero emission vehicle specifications (CARB, Site 1).

Some of extremely low emissions associated with fuel cell engines are a result of other required cleanup processes. For example, typical PEM fuel cell stacks require less than 10 ppmv CO in the feed stream or the anode gets "poisoned," resulting in lower output power. Fuel processors produce CO at levels from 2000 to 5000 ppmv, requiring CO removal as illustrated in Figure 7. Although there are many commercial methods available for CO reduction, they are unlikely candidates for fuel cell engines because of their complexity and low product recovery. Therefore, a considerable amount of ongoing research is being conducted to develop a suitable CO clean-up process. In one approach, a preferential oxidation reactor unit oxidizes CO with added air in preference to the H_2 in the fuel stream. Because some H_2 can be lost the process, it is very important to achieve the lowest practical concentration of CO in the shift reaction and the highest possible CO tolerance of the fuel cell's anode.

As noted above, the fuel cell stack can only consume around 85 percent of the H_2 delivered by the fuel processor. A combustor burns the excess H_2 from the anode exhaust and thereby delivers a clean exhaust stream from the system. The waste energy obtained from the combustor can be utilized in the fuel reforming process to aid in rapid warm-up (see Figure 7) and effective operation of the reformer. Additionally, this process can remove trace hydrocarbons and CO from the exhaust.

3.3 Hydrogen Production

The large-scale adoption of direct H_2-powered, FCVs would require a H_2 infrastructure be established to support the fuel demand. A variety of options exist for instituting H_2 as a transportation fuel. These choices impact efficiency, emissions, cost, and other factors. One of the primary decision points is where to produce the H_2. Options include off-site production at a centralized plant, on-site production at the fuel station, or at home. As with other transportation fuels produced off-site at centralized plants, H_2 must be transported by truck, rail, or pipeline to refueling stations. Production on-site requires the transport of the feedstock fuels—natural gas or methanol, electricity, and water—to the local fueling station where the hydrogen is then produced.

3.3.1 Description of the technology

Hydrogen can be produced (1) thermochemically from fossil fuels or biomass, (2) electrolytically from water, or (3) photolytically from water. The primary thermochemical method for H_2 production is steam/methane reforming (SMR). This process produces one mole of CO_2 for each four moles of H_2, but it also requires energy for the reaction to take place. Figure 10 shows a typical SMR flow diagram. The majority of the H_2 is formed in the reformer where methane (CH_4) reacts with water to form CO and H_2 in a high temperature, high pressure reaction. Heat from the exiting gases can be recovered to preheat the feed to the reformer. In the shift reactor, the CO is further processed with steam to form CO_2 and additional H_2. The pressure swing adsorber separates the CO_2 and unreacted methane and water to yield H_2 more than 99 percent pure.

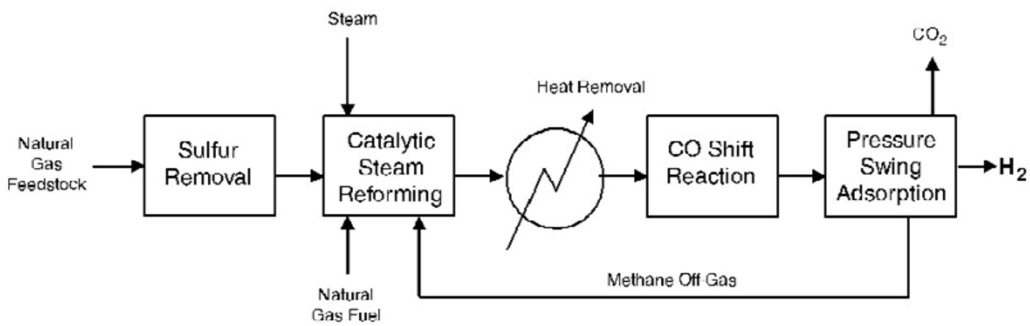

Figure 10. Steam Methane-Reforming Process Flow Diagram.

Currently, H_2 is used at the point of production for ammonia manufacture and petroleum refining with less than 5 percent distributed for off-site use. In a H_2 economy, SMR is proposed for off-site, centralized plants and for on-site fuel-stations. Figure 11 shows ranges of the capital investment costs for SMR with large capacities representative of centralized plants and smaller capacities applicable to on-site fueling stations.

As discussed above, the reforming process can also be used with methanol and gasoline to produce H_2. Another H_2 production option for biomass and coal feedstocks involves gasification to produce a syngas. The syngas can then be additionally processed thermochemically to increase the H_2 fraction. Other thermochemical technologies include

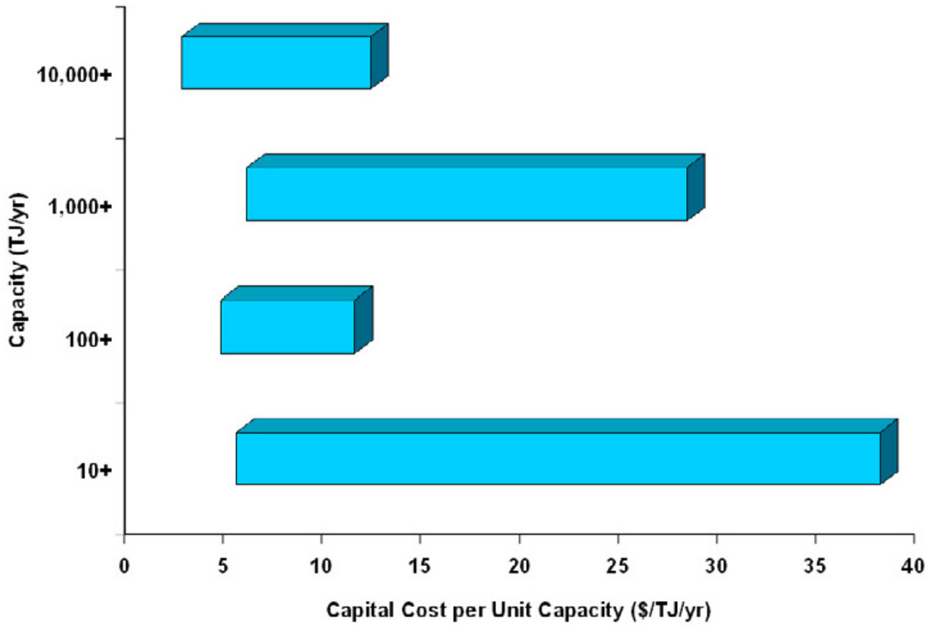

Figure 11. Range of Capital Investment Costs for Steam Methane Reforming.

(a) partial oxidation of hydrocarbons, (b) thermocatalytic decomposition of hydrocarbons, and (c) biomass or organic waste pyrolysis. Future H_2 scenario analyses may include some of these technologies.

The primary electrolytic process involves alkaline electrolysis. This process uses electricity to breakdown water into hydrogen and oxygen. In an alkaline electrolyzer, the electrolyte is concentrated potassium hydroxide. Electrolysis produces a low-pressure H_2 gas that must be compressed or liquified for transport and use. Electrolysis has been proposed as a production process for on-site fuel stations and at-home applications. Figure 12 shows ranges of capital investments for alkaline electrolysis stations. The emissions implications of electrolytically-produced H_2 are highly sensitive to the electricity generation method.

Another electrolysis process involves proton exchange membranes (PEM). This is basically a reverse process of the PEM fuel cell. In the electroylsis process, water is added on the positive side of the cell, and an electric charge is imposed across the membrane. This induces the movement of H_2 ions through the membrane to the negative side where they link up with electrons to produce H_2 gas. On the positive side, oxygen is expelled and replaced with more water.

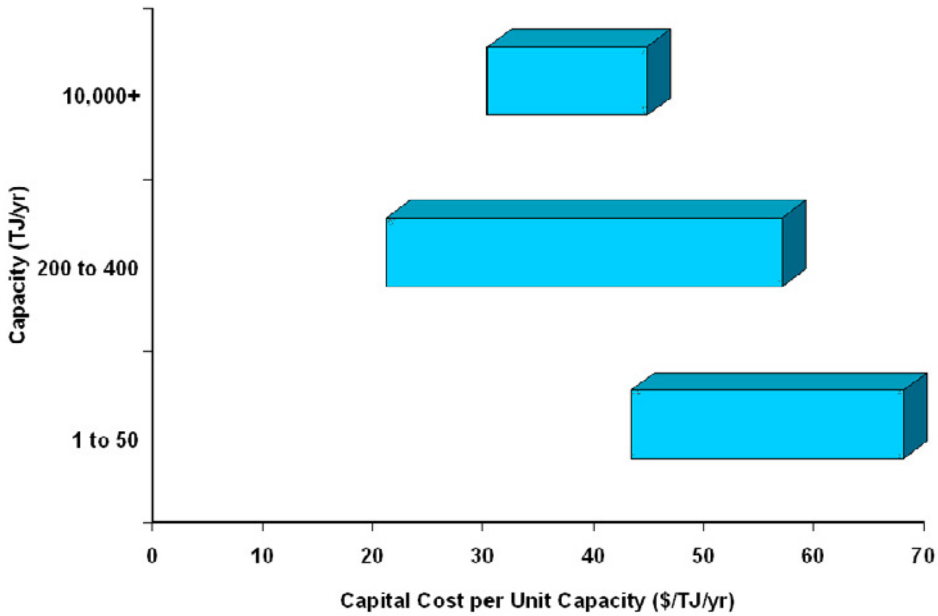

Figure 12. Range of Investment Costs for Electrolysis.

Photolytic processes are long-term possibilities for H_2 production. These options include (a) photobiological such as algal production and (b) photoelectrochemical production from water. These processes are still at the research stage, and their future practicability is unknown.

3.3.2 Issues for implementation

Distribution—Hydrogen as a liquid or a gas contains only 25 to 30 percent of the energy per unit volume of gasoline and natural gas. Thus, for centralized H_2 production, distribution (by truck, pipeline, or rail) presents substantial additional costs. In addition, there are significant costs in compressing or liquefying the H_2 for storage and subsequent distribution. Capital costs for this equipment are also significant.

With on-site production, distribution becomes an issue of the “H_2 carrier”. For example, methane is the H_2 carrier for the SMR process since the methane must be distributed to the fuel station for reforming. Other H_2 carriers include gasoline, methanol, and ammonia.

Storage—Another issue to resolve when using H_2 fuel is storage, which takes place first in the plant, second in the transport equipment (i.e., truck or rail when centralized plants are used), and third in the car itself. The low density of H_2 gas requires larger tank volumes for similar miles traveled when compared to petroleum. Transportation efficiencies can be improved by storing H_2 either (1) as a compressed gas, (2) as a liquified gas (with the associated additional energy requirements to liquify), (3) on metal hydrides, or (4) on carbon nanotubes. These approaches are not capable of completely offsetting hydrogen's energy density limitations, however. For example, for an equivalent energy content of gasoline, storage requirements for liquid H_2 and compressed H_2 gas are 6 to 8 times and 6 to 10 times more, respectively.

The hydride and nanotube H_2 storage options are adsorption processes. Hydrides require high temperature heat to release the adsorbed H_2, whereas lower temperatures may be required for release from nanotubes. Research on hydride and nanotube storage options is ongoing. See Section 4 for a discussion of how H_2 distribution and storage technologies have been mapped into the MARKAL modeling framework.

Natural gas availability and price—As discussed in Section 3.2.5, natural gas for SMR H_2 production would have to compete with existing and anticipated uses, particularly in the electricity generation sector. Hydrogen prices would also depend on fluctuations in natural gas price.

3.3.3 Emissions

Typical SMR process emissions are direct emissions from the process itself and indirect emissions at the power plant as a result of electricity requirements for the process. The primary direct emission is CO_2, which is the waste product of the reforming process. Other emissions include unreacted CH_4 and CO and small quantities of NO_2 and PM. For the electrolysis process, all emissions are indirect. As mentioned earlier, these will depend sensitively on the electricity generation method and will be significant when fossil fuels are the fuel choice for electricity generation. The use of renewable energy sources would appreciably reduce the environmental burden of the electrolysis process. Combined with zero emissions from direct H_2 FCVs, renewable-powered electrolysis has the potential for significant reductions in air pollution. However, this is widely expected to be the most expensive option for H_2 production in the near to midterm.

This section has touched upon many of the infrastructure requirements necessary for H_2-powered FCVs to be practical. Thus, any MARKAL scenarios in which H_2-powered fuel cells are considered would need to include a representation of a H_2 infrastructure. Section 4 describes the mapping of such an infrastructure into MARKAL. The approach demonstrates how geographical and demographic information can be used to inform the model.

Section 4
Mapping Hydrogen Infrastructure Technologies into MARKAL

An important factor in the adoption of H_2 fuel cell technologies is the existence of a cost-effective infrastructure for distributing H_2. Since it is not possible for such an infrastructure to quickly appear, one can expect a phased implementation. The early phase of a H_2 infrastructure development can consist of several technologies. This section provides an overview of the methodology used to characterize and map these technologies into the U.S. EPA MARKAL database. Critical implementation decisions and outstanding issues are identified. The methodology described here is important not only for modeling the H_2 infrastructure, but also serves as a template for modeling other geographically distributed resources within MARKAL. For this reason, more detail is provided regarding implementation than elsewhere in this report.

4.1 Overview

Hydrogen production may occur at a central location or at the refueling station. If centrally produced, such as by steam methane reforming, the H_2 fuel will have to be transported to demand centers via pipeline or truck. If by truck, this will likely require conversion of the H_2 from approximately 200 psi to a more dense form that is more cost-effectively transported. For the early-phase H_2 infrastructure development, truck transport of liquid H_2 is assumed. Alternatively, H_2 transport can be avoided by producing it directly at the refueling station (i.e., a gas station), either by electrolysis or steam methane reforming. In all cases, the H_2 fuel that is delivered to the vehicle is assumed to be compressed gas at 5000 psi. An additional alternative is the production of H_2 gas at residences. This process requires electricity to fuel electrolysis. Residential H_2 production can be performed continuously or only at night, when electricity prices are typically lower. In this phase of the analysis, vehicles are modeled with onboard storage of compressed H_2 gas. Future scenarios will consider additional onboard storage technologies.

Thus, the relevant technologies necessary to represent the H_2 infrastructure include

- Central steam methane reformer,

- Liquid H_2 trucking,
- H_2 gas pipeline,
- Steam methane reformer at the fueling station,
- Alkaline electrolysis at the station,
- Night-time only alkaline electrolysis at the fueling station,
- Electrolysis at residence,
- Night-time only electrolysis at residence, and
- Automotive fueling stations.

The linkages between these various H_2 technologies are represented in Figure 13.

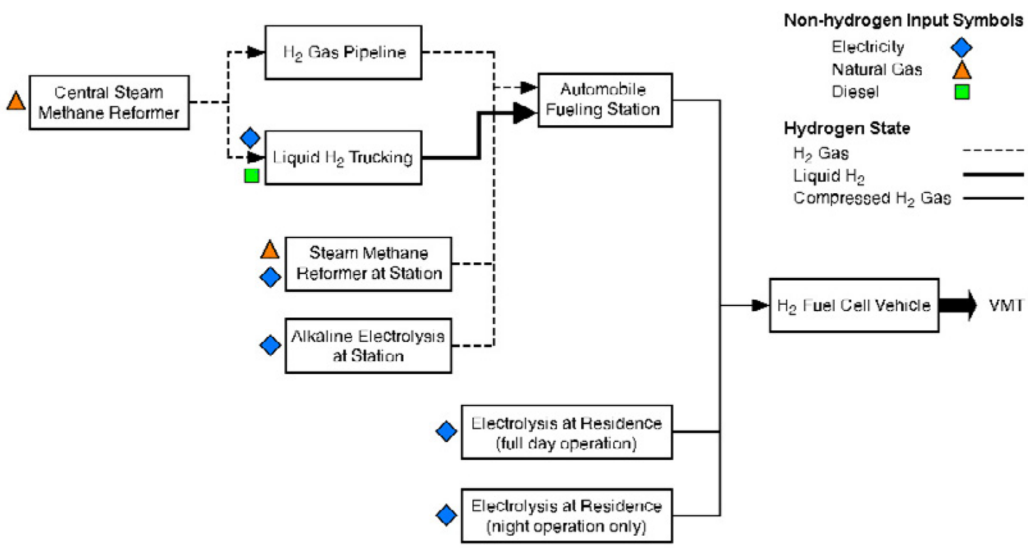

Figure 13. MARKAL RES Diagram for Centralized Steam Methane Reforming.

Although Figure 13 depicts one H_2 station (representing delivery to only a single population segment), the costs of making H_2 fuel available for use in FCVs is considered in the U.S. EPA database for 12 representative segments of the population. The characterization of these 12 representative population segments is shown in Table 4.

Table 4. Population Segment Definitions by Population and Distance.

Segment Number	Population Range		Distance from Central Plant		Number of Vehicles in Segment	
	Low End	High End	Low End	High End	2000 Census	%
1	500,000	infinity	0	30	52,934,840	62.6
2	100,000	500,000	0	30	1,374,163	1.6
3	50,000	100,000	0	30	1,421,821	1.7
4	100,000	500,000	30	60	4,338,047	5.1
5	50,000	100,000	30	60	4,121,994	4.9
6	100,000	500,000	60	120	5,487,342	6.5
7	50,000	100,000	60	120	6,009,105	7.1
8	100,000	500,000	120	240	3,315,001	3.9
9	50,000	100,000	120	240	4,048,789	4.8
10	100,000	500,000	240	480	580,851	0.7
11	50,000	100,000	240	480	837,577	1.0
12	50,000	100,000	480	960	100,979	0.1

The 12 population segments are not defined as specific geographical regions, but represent instead different population groupings that share similar characteristics. These characteristics include factors that affect the costs of H_2 distribution, specifically the size and density of the populations and proximity to central production facilities. The methodology for modeling H_2 production and delivery is discussed in the following section.

4.2 Methodology

Aspects of the methodology described here include: modeling transportation costs, locating centralized plants and refueling stations, calculating transportation distances, and characterizing trucking and pipelines.

4.2.1 Modeling hydrogen transportation costs

An important component of mapping the H_2 infrastructure into MARKAL was the characterization of the transportation costs for supplying H_2 to different segments of the population. This characterization was critical because distances to each refueling station may vary substantially and, because the costs of H_2 transport, may be a high portion of the overall costs of supplying H_2 to the vehicle. Hydrogen is more costly to deliver compared to other fuels such as gasoline because of its low energy density—even when compressed or liquefied.

The distance to each population segment is important to consider when evaluating the costs of transport from a central facility. In order to calculate the distances, it is necessary to know approximately where centralized plants and refueling locations will be located.

4.2.2 Central plant locations

An important factor in calculating transportation costs is the distance from a segment of the population to a centralized H_2 plant. The siting of such plants should include consideration of issues such as the location of feed stocks (e.g., electricity, natural gas, or diesel fuel) and the balancing of production and transportation costs. In the absence of better information, a heuristic approach has been applied to locate central plants.

An assumption in this heuristic approach was that central plants were assumed to be located in large urban areas. This assumption is reasonable because transportation costs would necessitate the location of central plants near larger centers of demand. An urban area is an official Census 2000 term that, in general, is a contiguous area that has a population density of greater than 1,000 people per square mile at the census block level.

In deciding where hydrogen plants might be located, the following guiding rule was adopted: a central H_2 production plant would serve at least 400,000 cars, equivalent to 165 tons of H_2 per day. This size plant is meant to equate roughly to a size that could achieve significant economies of scale.

A procedure was developed and followed to locate plants of this capacity or greater. Using Geographic Information System (GIS) tools, plants were located in central locations where at least 500,000 people would be served, corresponding to approximately 200,000 cars (assuming all cars were to use H_2). This cutoff of 200,000 cars is lower than the 400,000 value stated in the previous paragraph because it is assumed that these plants will also serve nearby areas with delivery by pipeline or truck. The additional H_2 demanded will raise the total demand to more than 400,000 cars.

Given this information, MARKAL will select the amount of centralized plant capacity based on numerous considerations, including factors unrelated to H_2 modeling (e.g., oil prices). Care therefore must be taken to confirm that the model results make sense (e.g., that a plant located in an urban area with 200,000 cars does indeed serve nearby areas). If not, the costing of the centralized plant may have to be adjusted.

4.2.3 Refueling station locations

The location of refueling stations is important for estimating trucking and long-distance pipeline distances, as well as for estimating the costs of local delivery by pipeline. In this study, H_2 refueling stations are assumed to be dispersed throughout the census-defined urban areas. This assumption is reasonable since according to Census 2000, 81 percent of vehicles (85 million of a total of 105 million) in the nation are owned by residents living within urban areas.

4.2.4 Distance calculations with GIS

GIS tools were used to approximate pipeline and trucking distances from the central plant to the refueling station. First, following the guiding rule for locating central plants, a database of central plant locations were identified and entered into a GIS map of the United States. Then, an ArcView layer of census-defined urban areas was added. Combined with the urban area map was a database indicating the size of each urban area. Using tools available in ArcView GIS, the fraction of the population falling within a certain distance range of a centralized plant and within a certain urban area size classification could be determined. The 12 population segments and their defining characteristics, population range, and distance range are presented in Table 4.

4.2.5 Trucking

The distances used to estimate truck transport costs to each population segment were based upon the distance intervals as given in Table 4. The distance to the population segment was evaluated as the midpoint of the interval. This estimate was doubled to account for an empty return trip. For example, for population segment 1, which was defined (in part) by a distance from the central plant of between zero and 30 miles, the midpoint is 15 miles. The round trip distance was assumed to be 30 miles.

The GIS procedure used rectilinear estimates of the distance, which will tend to under-estimate the total round trip distance. However, a greater portion of the urban area within the distance interval is assumed to be nearer to the central plant than the midpoint distance; this will tend to have the opposite bias. Thus, in the absence of more detailed information, the midpoint was selected.

The trucking option actually consists of a set of technologies. Trucking, as implemented in MARKAL, assumes that the H_2 produced at the central plant will be liquefied, placed into diesel-fueled tanker trucks, driven to the refueling station, volatilized, and dispensed to the H_2 vehicle. The costs and efficiencies of the entire trucking option reflect the costs and efficiencies of all of these processes.

4.2.6 Pipelines

Hydrogen can be transported via pipeline as an alternative to being trucked from the central plant to the fueling stations. Like the trucking option, this option represents all the processes involved with taking the H_2 in the form that it is produced at the central plant to its form as it is dispensed. Therefore, in addition to the pipelines and the associated right-of-ways, the pipeline option includes compressor stations along the way, compressing and dispensing equipment at the refueling station, and the associated energy requirements.

Delivery by pipeline can be simplified to consist of (i) delivery from a central plant to a city gate, followed by (ii) local distribution from the city gate to the refueling stations (Ogden 1999). In this study, the city gate corresponds to an urban area. The cost of long-distance transmission is primarily a function of the length of the pipeline to the gate and total demand of the urban area.

In this preliminary work, the length of a long-distance pipeline required to reach each urban area gate is approximated in the same fashion as for trucking, with the exception that pipelining is a one-way trip. If costs need to be more precisely estimated, a more detailed analysis could be undertaken to anticipate a more realistic layout of the networks, perhaps modeled on natural gas distribution networks. That kind of analysis, however, would involve more complexity than is warranted here because the costs of the long-distance transmission appear to be considerably less than the costs of local distribution (Ogden 1999).

According to Ogden (1999), the cost of local distribution (e.g., H_2 delivery from the gate to the refueling stations) is a strong function of the density of vehicles using H_2. The local distribution costs begin to rise sharply for areas with vehicle densities less than 300 cars per square mile. Above a density of 400 cars per square mile, the costs of local distribution per unit of energy transmitted begins to level off at roughly \$2/GJ of H_2 (Ogden, 1999). This cost estimate of \$2/GJ of H_2 assumes costs of \$1 million per mile of pipeline. If pipeline costs were \$250,000 per mile, then the costs would be somewhat lower, about \$1.5/GJ.

The above information is useful for estimating the costs of H_2 delivery to a census-defined urban area. The car density of an urban area has been reported to roughly correspond to the car density at which the pipelining becomes economical: 400 cars per square mile (Ogden 1999). Assuming the national average for car ownership, approximately 4 cars per 10 persons, the delineation of urban areas roughly corresponds to areas with vehicle densities of 400 cars per square mile (1000 times 4/10). Although this only applies to cars using H_2 fuel, Ogden (1999) also suggests that the pipelines are more economical if designed for a large and stable demand. Therefore, it is reasonable to assume that delivery will be carried out by truck until the time that the sufficient density of cars using H_2 is reached.

Information is not yet available that allows for adjustment of costs by the total demand of the urban area. For example, it should be less costly to deliver H_2 to refueling stations in large urban areas than small urban areas due to the nature of gas transmission economics. In the absence of such information, the estimate of \$2/GJ is used as the central estimate.

4.3 Implementation

After characterizing the various H_2 infrastructure technologies and population segments, the next step was to integrate this information into the MARKAL model. This involved modifying the RES to incorporate the relevant technologies and energy carriers for each population segment. Technologies included in the RES were those shown in Figure 13. Information about the cost and efficiency of fueling station equipment was included for each transportation technology. However, fueling stations were represented in the RES as dummy nodes that aggregate the amounts of H_2 produced via different options. Use of dummy nodes allowed the total dispensed amount for a population segment to be calculated and constrained.

Hydrogen-related energy carriers represented in the RES included H_2 as a gas, liquid, and compressed gas. Mass balances for each technology were created that take compression into account.

Next, efficiency and cost data for H_2 FCVs were characterized. Hydrogen FCVs were then added to the RES. In this implementation, H_2 fuel cell technologies were considered for the personal vehicle sector only. Hydrogen FCVs were then allowed to compete with other personal vehicle technologies to meet VMT demand.

In addition to this representation, several modeling issues were addressed with constraints in MARKAL. These included limits on VMT and rate of growth.

<u>VMT limits</u>—Hydrogen supplied to each population segment cannot exceed the total VMT demand for each segment. Appropriate MARKAL constraints were therefore necessary.

Rate of growth limits—Because of its linear programming formulation, MARKAL may predict a rate of vehicle adoption that is more rapid than is practical. For example, MARKAL does not model consumers' hesitation in purchasing a new, unproven technology or the need for a gradual ramp-up in manufacturers' production capacity. To represent these factors, a MARKAL growth constraint was used to limit the rate of growth. The growth constraint limited initial-year adoption to 1 percent of total personal vehicle VMT. Hydrogen FCV penetration was then restricted to grow by no more than 300 percent in the following 5-year period. In the next two 5-year periods, growth could be no more than 220 percent and 160 percent, respectively.

Other issues have been identified that may arise when modeling some technological scenarios involving a H_2 infrastructure. These issues include the interplay between trucking and pipelines, natural gas distribution, and the chicken-and-egg problem.

Chicken and egg problem—People will not purchase a new vehicle unless there is a place to refuel, but there will not be a place to refuel until there are people driving H_2 fuel cell cars. Often, the question is framed as, "How many initial stations are needed to overcome the chicken and egg problem?" (Melaina 2003) Thus, a small number of pre-existing stations may be required for some scenarios in order for growth to occur.

Trucking—Hydrogen transport via trucks is expected to precede use of pipelines, though the potential for pipelines to show up in the solution before trucks is possible. In cases where this arises, a constraint can be placed on the model forcing the early introduction of trucking.

Distribution of natural gas—Natural gas reforming of methane is limited by the capacity of the natural gas distribution network. A constraint could be added for each population segment that restricts the amount of H_2 to be produced from steam methane reforming.

Using the methodology and implementation described in this section, market penetration and demand for H_2 FCVs could be estimated for each of the 12 population segments, considering sector-specific characterizations of H_2 infrastructure costs. This methodology and implementation are preliminary, however, and are expected to be refined as the project progresses.

Section 5
Scenarios

5.1 Introduction

The previous sections provided a general introduction to the transportation technologies examined in this report, focusing on findings from the literature and how these conclusions are being mapped into the MARKAL database. This section serves as a bridge between this research and the model results discussed in Section 6 by describing a number of scenarios distilled from this background material. These scenarios serve as “what if” story lines that characterize possible technological futures for the transportation sector. It is important to stress that they should not be interpreted as predictions about technology parameters, rates of market penetration, or emission trajectories. Rather, the scenarios pose such questions as, “If the investment cost of a compact hybrid automobile is $30,000 in 2030, how much of the market do these vehicles capture?” Note that one may also work backward in an exploratory sense and ask, “What range of investment costs for a new hybrid compact yields a minimum market penetration of 25 percent for these vehicles in 2030?” MARKAL returns results as consequences about these particular assumptions as they play out in the model’s energy-economic framework (which serves as a “container” for a more comprehensive set of assumptions). The scenario assumptions, of course, are plausible, but should not be taken as an endorsement of a particular research finding or range of values.

Given what is known or can safely be assumed about the potential for alternative transportation technologies and the economic and lifestyle trends which drive transportation demand, the course of technological evolution over the next few decades will likely be bounded by two general scenarios. The first and most conservative of these bounds does not look much different from the present: gasoline continues to fuel most vehicles, with the gradual introduction of more advanced ICEs and gasoline-electric hybrid vehicles. The market penetration of each would be a function of its relative cost and efficiency, the price of gasoline, government policy, and consumer environmental concerns. Moving slightly away from this bound, one might see greater use of fuels such as diesel, natural gas, and methanol. Vehicle power trains and their supporting infrastructure, however, will look familiar near this end of the scenario spectrum.

The opposite end of the scenario spectrum sees a more radical shift in the transportation infrastructure, with a movement away from fossil fuels to a hydrogen-based economy. At the far end of this spectrum, for instance, vehicles would be powered by H_2 fuel cells. For this future to be realized, fundamental changes must occur in the supply and distribution networks, as well as in consumer acceptance of a vehicle technology quite different from that which has dominated transportation for the last century. The importance of niche markets (e.g., H_2 fuel cell buses) as proving grounds for the new technologies as well as the role of transitional technologies (e.g., gasoline fuel cells) would likely become apparent in the successful evolution to this future.

These bounds, of course, assume that the nature of transportation demand does not change. Individuals, for instance, continue to prefer the convenience of a personal vehicle, and freight continues to be moved by a combination of rail, air, and a surface truck fleet. Within these bounds, however, exists a range of technological paths, with significant implications for the future use of fossil energy as well as the nature of atmospheric pollutant and greenhouse gas emissions. Although the particular path that transportation technologies take will be influenced by political, economic, and social factors that cannot easily be captured in a model like MARKAL, the modeling framework can be used to explore why one path (all other things being equal) might be preferred over another.

This report begins such an analysis by examining two general sets of scenarios: a series of “Evolution as Usual” (EAU) developments concerned with the continued advancement of conventional ICE and hybrid transportation technologies, and an “Early Phase Hydrogen Economy” (EPHE) transition that builds on the EAU assumptions to examine how the transformation to a hydrogen-based economy would affect transportation. Note that the present analysis does not give full consideration to interactions with model variables outside the transportation sector of the economy (which is particularly important with regard to the supply of alternative fuels). As discussed in Section 7, Future Work, this more comprehensive analysis is the goal of the TACT project, but awaits completion and refinement of the full MARKAL database. This report aims to provide a rigorous, though restricted, demonstration of the model’s capabilities.

5.2 Evolution-as-Usual Scenarios

Section 3 described the present set of personal vehicle technologies included in the MARKAL database. The model characterizes each technology by its availability date, investment cost, fixed and variable operating costs, efficiency, discount (hurdle) rate, growth rate limit, and emission factors for a range of pollutants (see Appendix A for a full description of the TACT MARKAL database and model). In addition to variations in these technology-related parameters, assumptions about the price of transportation fuels (including applicable taxes) provide the basis of the EAU scenarios described here. Note that transportation demand projections are fixed, including demand for particular vehicle classes (i.e., consumer preferences for compacts, fullsize cars, minivans, pickups, and SUVs do not vary across the EAU scenarios). Table 5 summarizes these exogenous vehicle demand assumptions used in the MARKAL database. Travel demand is denoted in billion vehicle miles traveled (BVMT). Note that while AEO-derived demand projections are employed here, future analyses will consider alternative travel demand projections and examine sensitivity to these assumptions.

The EAU scenarios focus on those factors driving the balance between gasoline-fueled ICE vehicles (conventional and advanced mpg) and gasoline-electric hybrids. Relative to conventional gasoline-fueled vehicles, their advanced counterparts achieve a 14–23 mpg efficiency improvement, while 2X and 3X hybrids represent 100 and 200 percent increases in mileage, respectively. For the purposes of this report, both hybrid technologies are assumed to meet SULEV emission criteria. All ICE and hybrid engine technologies are available across the five vehicle classes (Table 5). Future EAU scenarios will examine additional transportation technologies, including gasoline and methanol fuel cells as well as the use of compressed natural gas (CNG), liquefied petroleum gas (LPG), ethanol, and methanol as fuels. Data for these technologies are not final, and their integration in the current MARKAL database is incomplete. Note that electric-powered vehicles remain in the EAU scenarios though, as parameterized, cannot compete with more conventional technologies and, therefore, do not enter the market.

Table 5. Transportation Demand Projections by Vehicle Class and Year.

Vehicle Class	Percent	Annual Demand (in BVMT) for year						
		2000	2005	2010	2015	2020	2025	2030
Compacts	25.0	585.9	665.8	746.4	830.8	909.2	994.1	1086.7
Full Size	26.9	629.5	715.3	801.9	892.5	976.7	1067.9	1167.5
Minivans	7.4	172.0	195.4	219.1	243.9	266.9	291.8	319.0
Pickups	19.7	461.2	524.1	587.6	654.0	715.7	782.5	885.4
SUVs	21.0	490.7	557.6	625.1	695.8	761.4	832.5	910.1
Total	100.0	2340	2659	2981	3318	3631	3970	4340

Several considerations drove selection of the EAU scenarios, including a desire to calibrate the MARKAL model to the EIA's AEO transportation results, a question about the conditions under which hybrid vehicles achieve significant market penetration, and an interest in the effects of sustained changes in gas prices. The model parameters varied and ranges of values explored—including those that were adjusted without appreciable effect—are discussed where relevant. Table 6 summarizes the EAU scenarios.

Table 6. Summary of the Evolution as Usual Transportation Scenarios.

EAU Scenario	Description
Hybrid Market	Examines the vehicle-specific factors driving hybrid market penetration while competing with conventional technologies
Conventionals Dominate	Examines the circumstances under which alternative vehicle technologies do not penetrate the transportation market
Hybrid Market without Conventionals	Assesses hybrid market penetration when manufacturers phase out conventional vehicles by 2020
2X Hybrids	Explores the conditions under which high-efficiency hybrids (3X) do not enter the market
Gas Price Variation	Investigates the effects of higher gas prices

5.2.1 Hybrid Market [HM(C)] Scenario

The EAU Hybrid Market [HM(C)] scenario examines the impact of moderate hybrid growth under competition with conventionals. The success of hybrid vehicles will depend largely on their cost and performance relative to ICE-powered vehicles—including advanced efficiency (miles per gallon)—and various "green" alternatives, consumer attitudes regarding the environment and adoption of new technologies, manufacturing capacity, and fuel costs. Hybrid market penetration in the MARKAL model scenarios will therefore be a function of hybrid investment costs and operating efficiencies, the particular discount, or hurdle, rate applied to the technology, growth constraints on hybrid penetration, and gasoline prices. The remainder of this section describes the parameter settings relevant to the EAU Hybrid Market Scenario. Detail on parameters not varied here is also provided as changes in their values lie behind the storylines of the subsequent EAU scenarios.

The cost to purchase a hybrid vehicle and the savings in fuel costs (a function of engine efficiency) the technology offers will be dominant parameters driving hybrid market penetration. Future hybrid investment costs and efficiencies will be a function of technical advances (the learning that takes place in design and manufacturing), sales volumes (economies of scale), and targeted government subsidies. Starting with the OTT QM parameters, the

HM(C) scenario assumed values of these parameters that yielded moderate hybrid growth in 2030. By way of illustration, Table 7 compares 2X and 3X hybrid technology parameters for compact vehicles with their conventional and advanced ICE counterparts, as well as AEO values. Note that the numbers used here are at the low end of the spectrum summarized from the literature in Section 3 of this report.

Table 7. Compact Vehicle Technology Parameter Values for HM(C) Scenario.

Vehicle Type	Period beginning in Year						
	2000	2005	2010	2015	2020	2025	2030
Investment Cost ($1000, 1999)							
2X Hybrid	25.31	25.31	24.77	24.10	23.76	22.27	22.27
3X Hybrid	NA[a]	NA	NA	26.20	25.46	23.34	23.34
Conventional ICE	19.25	20.24	20.64	20.96	21.21	21.21	21.21
Advanced ICE	NA	NA	22.25	22.59	22.86	22.86	22.86
AEO Hybrid	26.89	26.89	22.74	22.25	22.62	[b]	[b]
Efficiency (mpg)							
2X Hybrid	44.50	44.50	55.21	60.27	64.52	68.82	68.82
3X Hybrid	NA	NA	NA	79.72	92.90	103.23	103.23
Conventional ICE	31.02	23.96	34.50	34.44	34.41	34.41	34.41
Advanced ICE	NA	NA	54.17	54.07	54.02	54.02	54.02
AEO Hybrid	46.36	45.10	44.33	43.79	43.64	[b]	[b]

[a] NA = not available in this time period.
[b] AEO 2002 data available only to 2020.

HM(C) includes two sub-scenarios designed to explore the factors driving ICE-hybrid competition. The first of these examines the effects of a 10 percent reduction in 2X hybrid investment costs (approximately $2500) offered during the first two model periods, a discount roughly equivalent to the tax break currently available on US hybrid vehicle purchases. The second sub-scenario adds a 16 percent mark-up on advanced efficiency ICE vehicles—the increase needed to reduce the alternatives to a choice between conventional ICE and hybrid vehicles.

Beyond cost considerations, consumer demand for hybrids will depend on the willingness of vehicle owners to invest in a new and unproven technology, a perceptual issue that the model captures through a technology-specific discount rate (i.e., a risk premium). The HM(C) scenario maintains the model's 5 percent discount rate for all technologies, though this is varied in subsequent EAU scenarios.

Even with rapid acceptance and an affordable sticker price, a rapid transition to hybrid vehicles is unlikely. The natural turnover of the existing (conventional ICE) vehicle fleet will slow hybrid penetration, as will the inability of manufacturers to retool assembly lines overnight regardless of demand. The model captures this inertia through a growth rate constraint that caps hybrid vehicle miles traveled in a given period at a declining percentage of the previous period's available capacity (see Table 8). 2X Hybrids can enter the market at 0.5 percent of demand for each vehicle class during the first period of their availability (2000), while 3X hybrids are limited to 1.0 percent when introduced in 2015. Note that the growth rate constraints apply only to hybrid vehicles and do not affect conventional or advanced ICE technologies.

Table 8. Hybrid Vehicle Growth Constraints.

	Period Beginning in Year				
	2010	**2015**	**2020**	**2025**	**2030**
Growth Constraint (% of prior period utilization)[a]	200	120	60	30	30

[a] Per period growth is constrained to the given percentage of the previous period's available capacity.

Finally, gasoline prices will influence hybrid-ICE competition. The extent to which fuel savings compensates for the greater hybrid investment cost, given that hybrid gasoline consumption is equally affected by higher prices, is the focus of a subsequent EAU scenario. The HM(C) Scenario maintains the model's average $1.5 gasoline price.

The following sections describe the remaining EAU scenarios. For the sake of brevity, only significant departures from the parameter settings described above are discussed. It is therefore tempting to think of the EAU HM(C) Scenario as a "base" or "reference" case. The TACT team, however, cautions against this interpretation. The HM(C) numbers represent one possible view of the future, selected in this case to examine the potential for moderate hybrid growth in an overall transportation scenario similar to the AEO. This state of the world is a consequence of model assumptions, the selection of which was driven by particular questions. The assumptions and results are no more (or less) likely than those that follow from the other EAU scenarios. Attention should be focused on the validity of the particular questions and assumptions, rather than on endorsement of particular results.

5.2.2 Conventionals Dominate (CD) Scenario

The EAU Conventionals Dominate (CD) Scenario represents a replication of the EIA's AEO transportation reference case. Exact replication of the AEO numbers, of course, is neither possible nor desirable. The AEO, however, is a widely cited standard, and therefore serves as a useful check on the TACT modeling results. Similar findings provide confidence in the MARKAL model's input and structural assumptions, while divergences offer a chance to explore how differences between TACT and AEO assumptions affect scenario outcomes. Note that the AEO time horizon is 20 years, whereas the MARKAL database currently extends to 2035. Section 6 takes this into account in its comparison of model scenarios.

The AEO reference scenario describes a world in which advanced technologies play a marginal role in meeting transportation demand (hybrids, for instance, achieve a market share of just under 2 percent in 2020). One can image at least three situations under which all advanced efficiency vehicles like hybrids might fail to achieve a significant market share, leaving conventional ICE technologies to meet transportation market demand (once again, future EAU scenarios will broaden the alternatives to include fuels other than gasoline). Consumers, for instance, may prove reluctant to adopt a new technology, a preference reflected in a higher associated discount rate. The Conventionals Dominate scenario, therefore, examines the effects of a 12 percent hurdle rate on both advanced efficiency ICE and hybrid vehicles—a 7 percent risk premium on the 5 percent rate applied to conventional vehicle technologies (12 percent was found to be the minimum discount rate that eliminated hybrid penetration).

The analysis explores the remaining situations in which conventional vehicle technologies might dominate as alternative hypotheses. The first of these sub-scenarios examines the effect of higher vehicle purchase prices—in this case, an across-the-board 15 percent mark-up in advanced efficiency ICE and hybrid investment costs. In contrast, the second alternative strikes at the primary (economic) advantage all advanced technology technologies offer—their greater efficiency and consequent fuel cost savings. Very low gas prices, if sustained, would discourage the purchase of advanced efficiency ICE and hybrid vehicles. The analysis, therefore, looks at the impact of a long-term $1.00/gallon gas price (a $0.50/gallon reduction from prior assumptions).

5.2.3 Hybrid Market Without Conventionals (HM) Scenario

The counterpart to the EAU Conventionals Dominate Scenario is one in which vehicle manufacturers and buyers make a complete switch to hybrid technologies. It is conceivable that, with proven reliability and reasonable cost, hybrid engines become the new conventional transportation technology. Manufacturers would realize the savings of tooling their assembly lines for a single technology, which would help bring costs in line with traditional ICE vehicles. Such a transition might be seen as part of the natural evolution of transportation technologies, even if consumers did not demand the fuel savings and environmental benefits of hybrid engines. The EAU Hybrid Market Without Conventionals (HM) Scenario therefore examines the impact of phasing out (via a model constraint) all conventional vehicles in 2025. Note that the entry rate on the 2X hybrid growth constraint had to be increased from 0.5 to 1.0 percent of the initial period demand in order to allow sufficient market penetration in subsequent years.

5.2.4 2X Hybrid (2xH) Scenario

The MARKAL database currently includes two hybrid vehicle types, characterized by their efficiencies relative to their ICE counterparts. These hybrid options are available across vehicle classes, though their availability dates differ; see Table 7. 2X hybrids, with a 100 percent efficiency improvement on ICE vehicles, are available in 2000, while their 3X higher-efficiency counterparts can enter the transportation market in 2015. The 2X Hybrid (2xH) Scenario examines hybrid market penetration when only the 2X option is offered. This scenario therefore represents a situation where the performance of hybrid engines remains below the more optimistic goals set by the U.S. DOE.

5.2.5 Gas Price Variation (GP) Scenario

Finally, hybrids offer the perceptual advantage of owning an environmentally-friendly vehicle. More pragmatically, of course, their greater efficiencies will yield long-term savings in fuel costs. The attractiveness of hybrids relative to standard ICE-powered vehicles might, therefore, be expected to increase with the price of gasoline. The extent to which this advantage is realized, however, depends on both vehicle efficiency and the extent to which owners value future operating cost reductions vis-à-vis a more immediate increase in purchase price (a function of the potential buyer’s implicit discount rate). The Gas Price Variation (GP) Scenario approaches this issue by examining how a gas price of $4.5/gallon affects the conventional-hybrid balance.

Section 6 discusses results from each of these EAU storylines. Once again, the goal is not to present a favored view of the world either in terms of model inputs (how hybrid vehicles, for instance, might be expected to perform in 2030) or outputs (the shape of the transportation sector’s emission trajectory). Each storyline corresponds to a particular question, and the value lies not in an isolated set of results, but in comparing answers across scenarios.

5.3 Early Phase Hydrogen Economy Scenarios

The EAU scenarios focused exclusively on factors that might shift the balance between future ICE and hybrid vehicle market penetration. The EPHE scenarios build on this analysis by adding H_2 fuel cells as a third high-efficiency vehicle technology. In the long-term, several drivers may lead the transportation sector to adopt H_2 as a fuel, including a potential need to

- achieve further reductions in environmental emissions,
- reduce the transportation sector's reliance on oil imports,
- reduce GHG emissions through sequestration of carbon dioxide at a centralized fossil fuel-based H_2 plant, and
- shift the fuel for future vehicles from fossil fuels to renewable resources.

The EPHE scenarios do not explore these drivers directly. Rather, they seek to examine the near-term consequences of introducing H_2 as a fuel in the U.S. transportation sector and, therefore, estimate the added costs of adopting H_2 fuel cell vehicles. In addition, because there are virtually no tailpipe emissions from H_2 FCVs, the reduction in transportation sector emissions will reflect the avoidance of emissions from vehicles displaced by their H_2 equivalents. In the next phase of this work, TACT will examine emissions from a complete life cycle perspective, one that fully accounts for the possible increase in emissions associated with H_2 production. The MARKAL modeling framework is uniquely suited for this type of systems-level assessment.

The full set of assumptions behind the EAU scenarios apply to the EPHE storylines. The EPHE scenarios, however, go beyond a focus on vehicle technologies and examine the makeup of the H_2 infrastructure. Centralized facilities, for instance, might produce H_2 for distribution to refueling stations by truck or pipeline; alternatively, refueling stations might produce H_2 on-site by electrolysis or steam methane reforming. Section 4 described how the EPHE H_2 infrastructure has been mapped into the MARKAL framework, and the three sets of EPHE scenarios include assessment of these infrastructure differences and their impact on resource consumption. Table 9 and the following sections summarize the EPHE scenarios. Future TACT work will examine additional H_2 production pathways and a wider variety of parameter values for H_2 production and distribution technologies.

5.3.1 Hydrogen Market Scenario (H2M)

Equivalent to the EAU Hybrid Market Scenario with Conventionals [HM(C)], H2M examines the effects on ICE and hybrid vehicle market shares, as well as emissions, for a moderate H_2 fuel cell market penetration. Tables 10 and 11 show the parameter values for

Table 9. Summary of the Early Phase Hydrogen Economy Transportation Scenarios.

EPHE Scenario	Description
Hydrogen Market	Examines the impact of a moderate H_2 fuel cell vehicle market penetration
Optimistic Hydrogen	Assesses the impact of optimistic H_2 production and distribution efficiencies as well as H_2 vehicle costs and efficiencies
Hydrogen Forcing	Forces the VMT by H_2 FCVs in year 2030 and beyond to be greater than or equal to some fraction (e.g., 10%, 20%, 30%, 40%, 50%) of the total 2030 demand

the compact H_2 FCVs used in the H2M scenario. Note that, although compact FCVs do not become available until 2020, larger classes (for which design issues are simpler to resolve) are available in 2015. Table 12 summarizes the assumptions associated with H_2 production. For the purpose of emission calculations, H_2 FCVs are treated as zero-emission vehicles.

Table 10. Compact Vehicle Technology Parameter Values for H2M Scenario.

Vehicle Type	Period beginning in Year						
	2000	2005	2010	2015	2020	2025	2030
Investment Cost ($1000, 1999)							
H_2 FCV	NA[a]	NA	NA	NA	27.58	24.4	24.4
AEO H_2 FCV	NA	84.46	50.94	34.73	27.11	[b]	[b]
Efficiency (mpg gasoline equivalent)							
H_2 FCV	NA	NA	NA	NA	92.9	103.23	103.23
AEO H_2 FCV	NA	50.94	49.73	48.99	48.43	[b]	[b]

[a] NA = not available in this time period.
[b] AEO 2002 data available only to 2020.

Table 11. Fuel Cell Vehicle Growth Constraints.

	Period Beginning in Year				
	2010	2015	2020	2025	2030
Growth Constraint (% of prior period utilization)[a]	200	120	60	30	30

[a] Per period growth is constrained to the given percentage of the previous period's available capacity.

Table 12. Hydrogen Production Parameter Values for H2M Scenario.

Description	1999 $Million/PJ/yr	
	Investment Cost	O&M Costs
Central steam methane reformer	20.56	1.88
Steam methane reforming at station	87.71	3.86
Alkaline electrolysis at station	65.39	0.31
Alkaline electrolysis at station (night operation only)[a]	130.78	0.31
Electrolyzer - residential (24 hour operation)	124.66	3.05
Electrolyzer - residential (night-only operation)[a]	249.33	3.05

[a] Because equipment capacities are measured in petajoules of output per year, equipment designated for night only operation has twice the investment cost.

5.3.2 Optimistic Hydrogen Scenario (H2O)

The EPHE H2O scenario investigates a future of faster movement towards a H_2 economy by examining the impact of optimistic assumptions regarding H_2 FCV costs and efficiencies. In this scenario, research finds cost effective solutions to H_2 storage and transport issues, and manufacturing develops cheaper fuel cell stacks making cars more cost competitive. Success in the FCV market thus encourages implementation of the necessary infrastructure.

5.3.3 Hydrogen Forcing Scenario (H2F)

Without major scientific breakthroughs or very large subsidies, H_2 is not likely to be competitive as a transportation fuel in the near term. The EPHE H2F scenarios, therefore, force a H_2 FCV market share in 2030. The scenarios, which look at penetration rates ranging from 10 to 50 percent (in 10 percent increments), capture potential shifts between electrolysis and steam methane reforming as sources of supply for an increasing H_2 demand. The associated changes in gasoline and natural gas consumption are of particular interest.

Section 6
Scenario Results and Analysis

The previous section identified several known factors that will shape the path along which transportation technologies evolve. Different combinations of these factors yielded possible futures and the section translated the resulting storylines into specific MARKAL scenarios. This section takes the conditions outlined in each scenario as a set of starting assumptions and examines their consequences as they play out in the MARKAL modeling framework. The first two sections examine the Evolution as Usual (EAU) and Early Phase Hydrogen Economy (EPHE) results, respectively. The third section approaches the long-term goal of the TACT project by offering a comparative analysis of these futures. When complete, the MARKAL database will allow an integrated assessment of all transportation technologies and will identify optimal paths based on their full life cycle implications—how the consequences of meeting a given level of transportation demand cascade through the entire energy economy.

6.1 EAU Scenario Outcomes

The goal of the TACT assessment is a comparative analysis of possible futures; hence, this section is organized around results, not specific EAU scenarios. Three sets of transportation scenario outcomes are of interest within the larger scope of this report: the particular technology paths along which transportation demand is met through 2030, the corresponding levels of fuel consumption, and the emission profiles that follow. As described in Section 5, the EAU scenarios focus on the circumstances driving the competition between conventional and advanced ICE vehicles and their hybrid counterparts. Attention should, therefore, be focused on how the conditions outlined in each scenario affect the choice of vehicle technology and resulting demand for gasoline and then on how the extent to which hybrid vehicles enter the market affects transportation-related emissions.

Figures 14 through 18 show how individual vehicle technologies contribute to meeting demand across time in terms of vehicle miles traveled for each EAU scenario, while Figures 19 through 23 express the same information as a percentage of per-period demand. Comparisons across scenarios are made in Figures 24 and 25 where market penetrations for

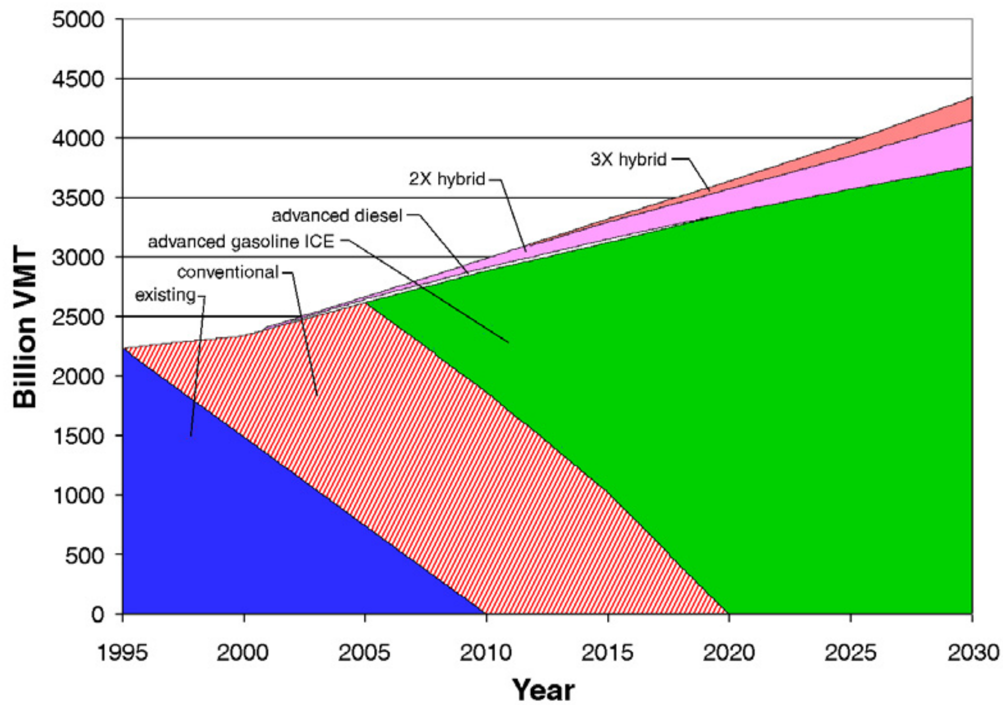

Figure 14. Per-period VMT of each Technology for the HM(C) Scenario.

advanced ICE vehicles and hybrids (2X and 3X combined), respectively, are shown in 2020 and 2030. Although the TACT project is ultimately concerned with emissions several decades out (2030 in this report; 2050 in future analyses), the evolution of transportation technologies between now and then is of interest because it will affect overall fuel consumption and, hence, aggregate emissions.

The most fundamental question to ask of these results is simply what shifts the balance between ICE-powered vehicles and hybrids in favor of the latter. The Hybrid Market Scenario [HM(C)] was derived from OTT assumptions about future transportation technology costs and performance and illustrates moderate hybrid growth (Figure 14). By 2030, hybrids meet approximately 13 percent of demand, with 2X vehicles accounting for two-thirds of the hybrid market share. Advanced efficiency ICE vehicles meet the remaining transportation demand.

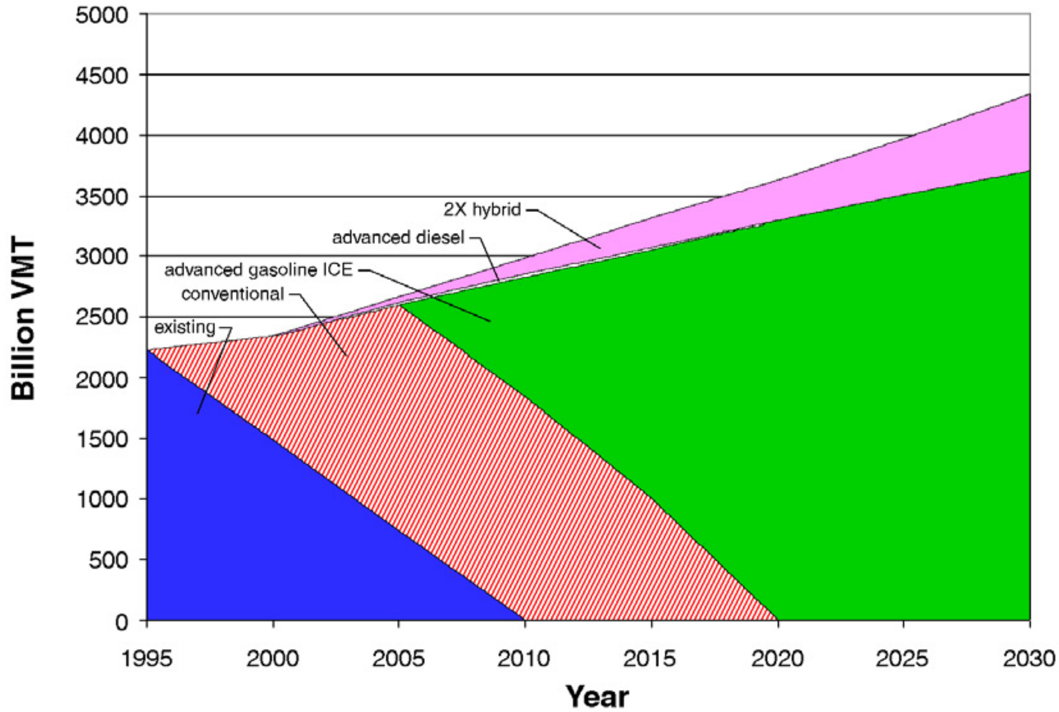

Figure 15. Per-period VMT of each Technology for the 2XH Scenario.

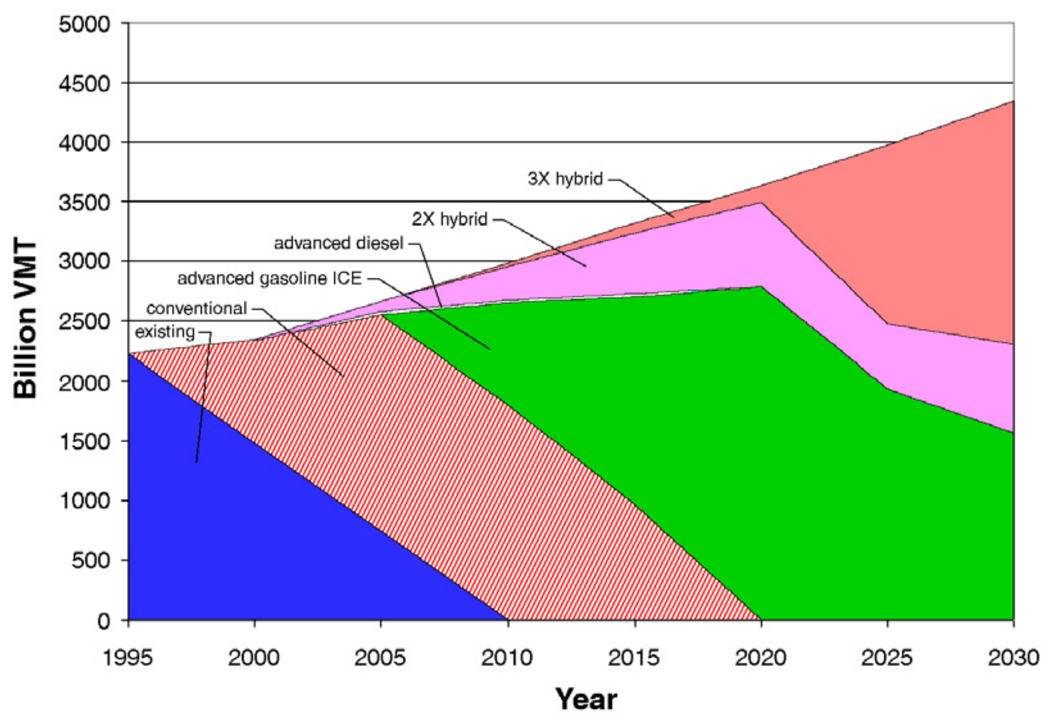

Figure 16. Per-period VMT of each Technology for the GP Scenario.

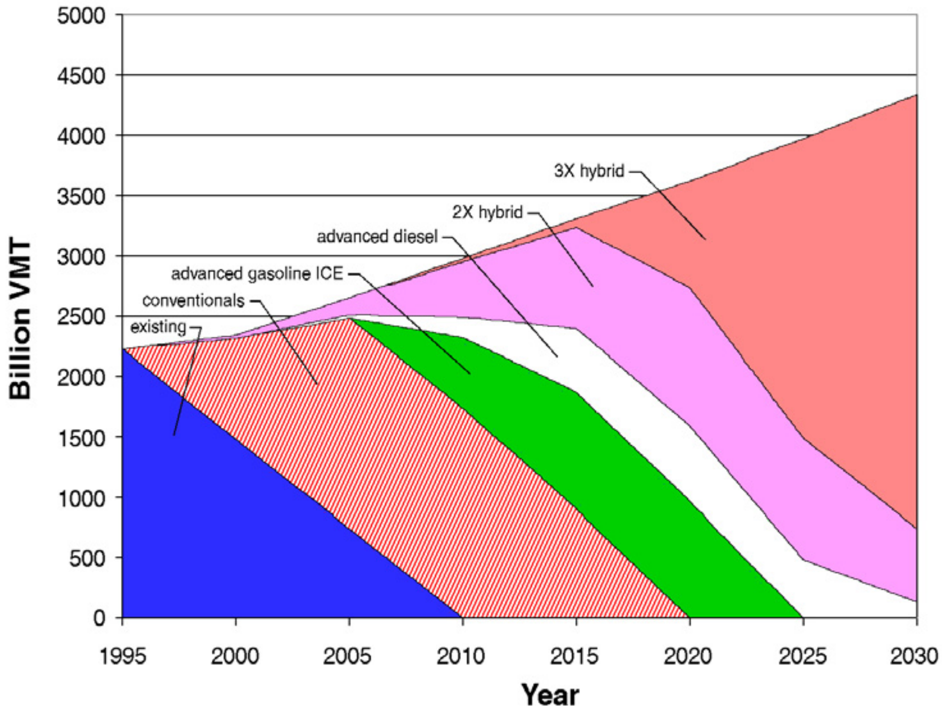

Figure 17. Per-period VMT of each Technology for the HM Scenario.

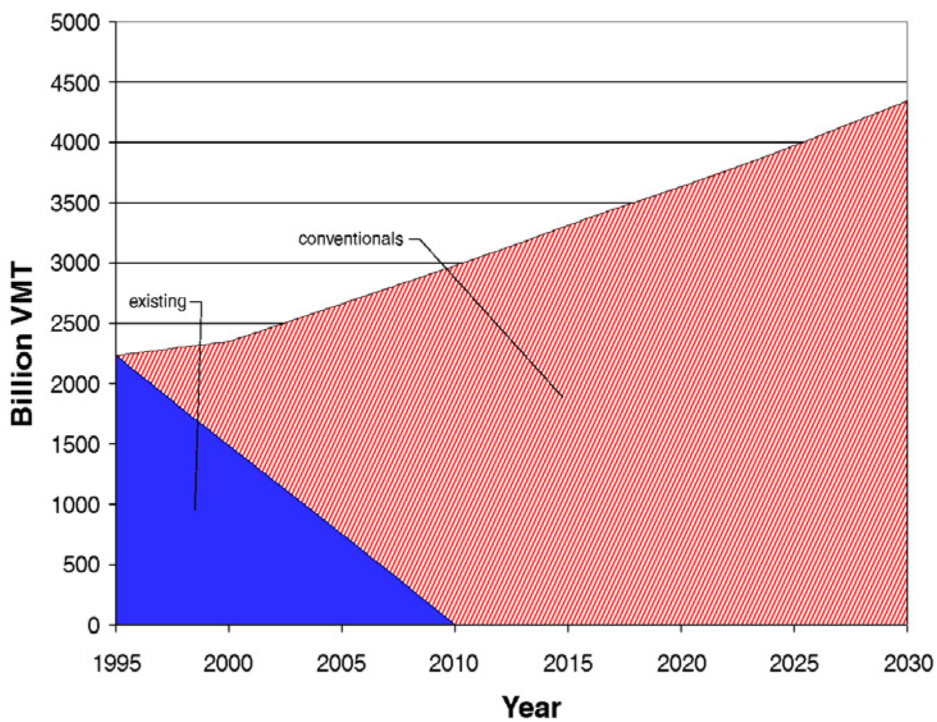

Figure 18. Per-period VMT of each Technology for the CD Scenario.

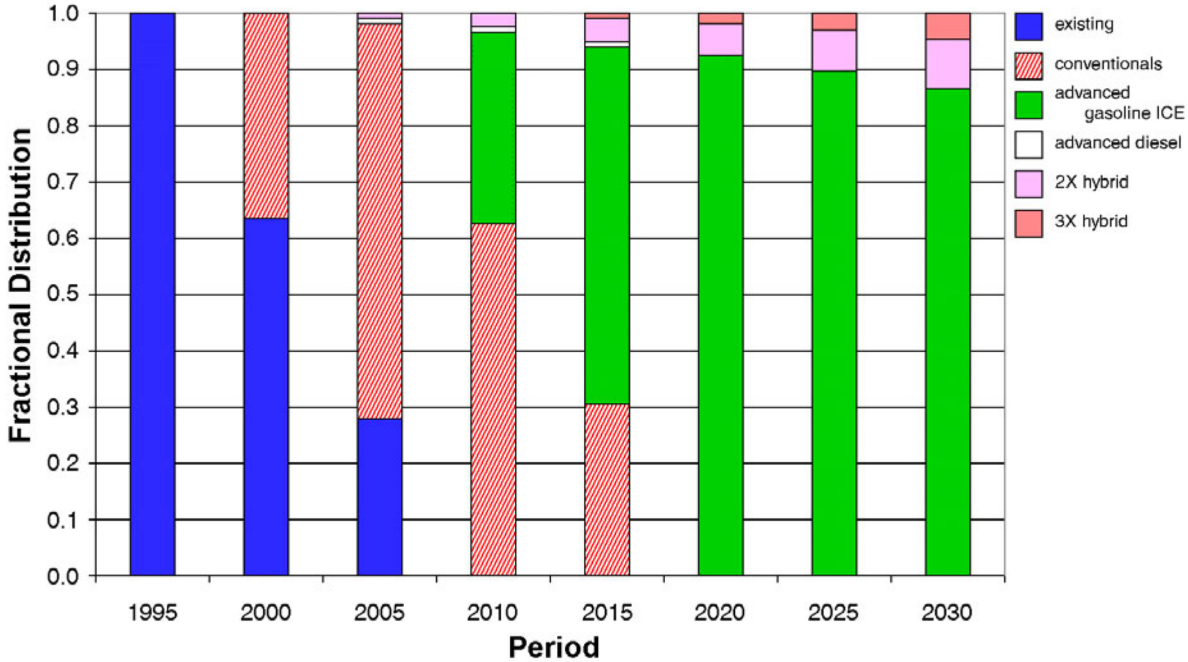

Figure 19. Technology Penetration per Period for HM(C) Scenario.

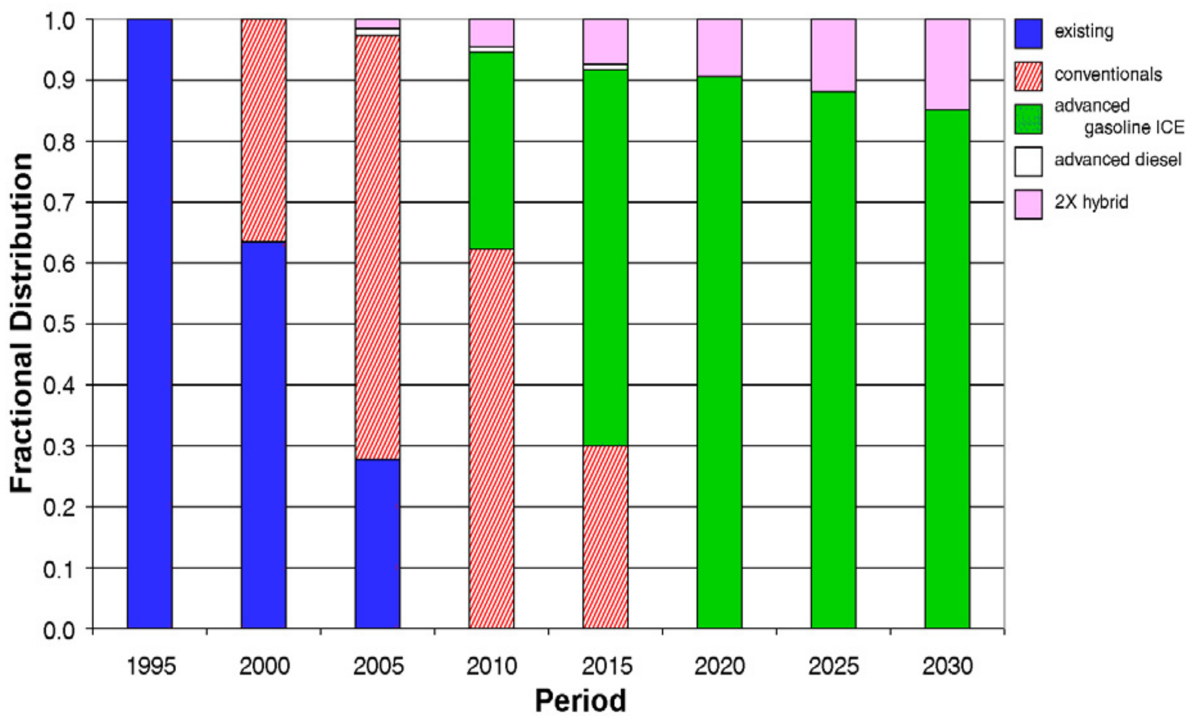

Figure 20. Technology Penetration per Period for 2XH Scenario.

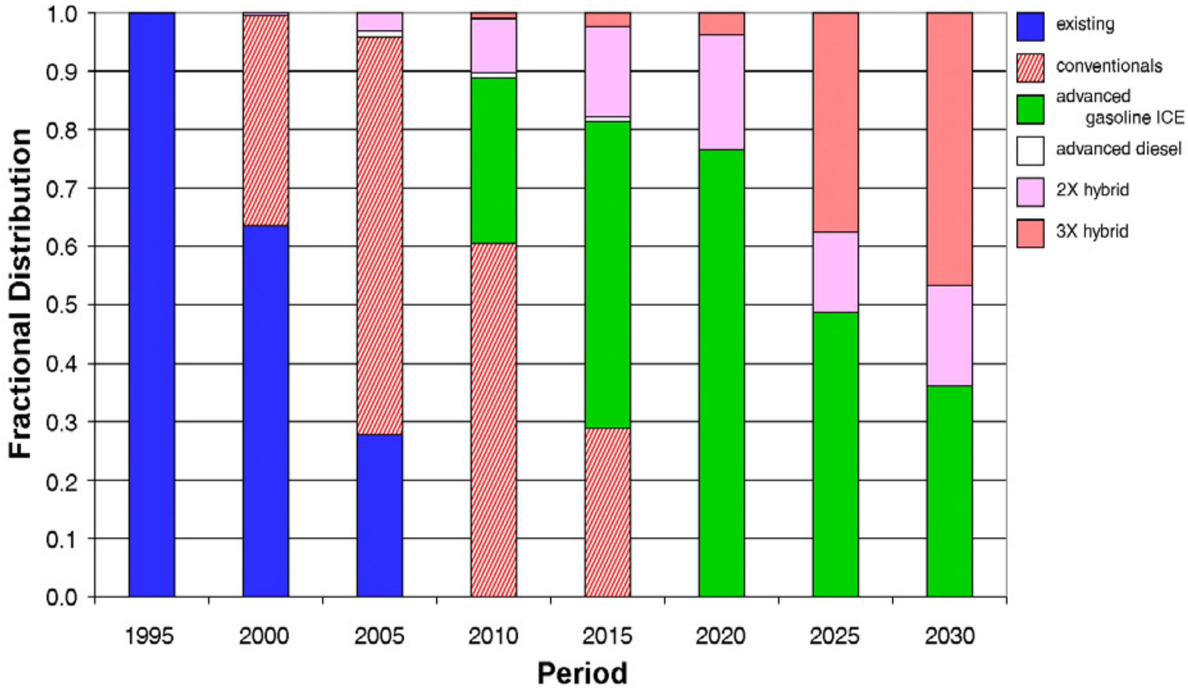

Figure 21. Technology Penetration per Period for GP Scenario.

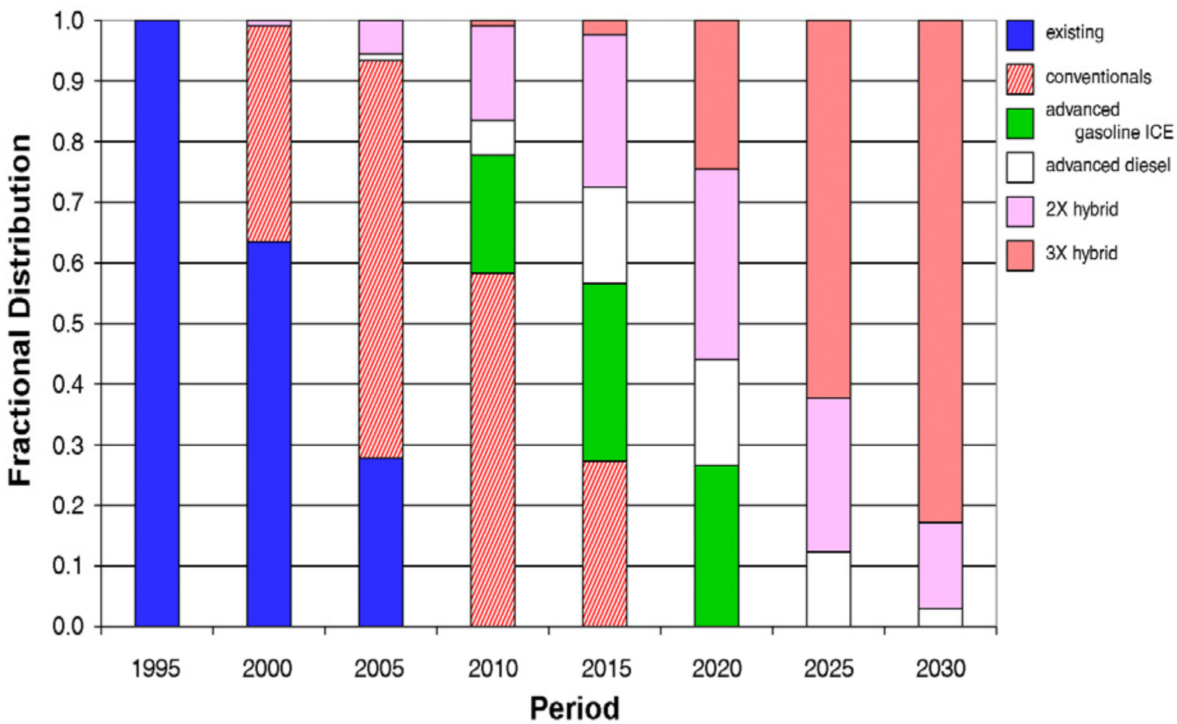

Figure 22. Technology Penetration per Period for HM Scenario.

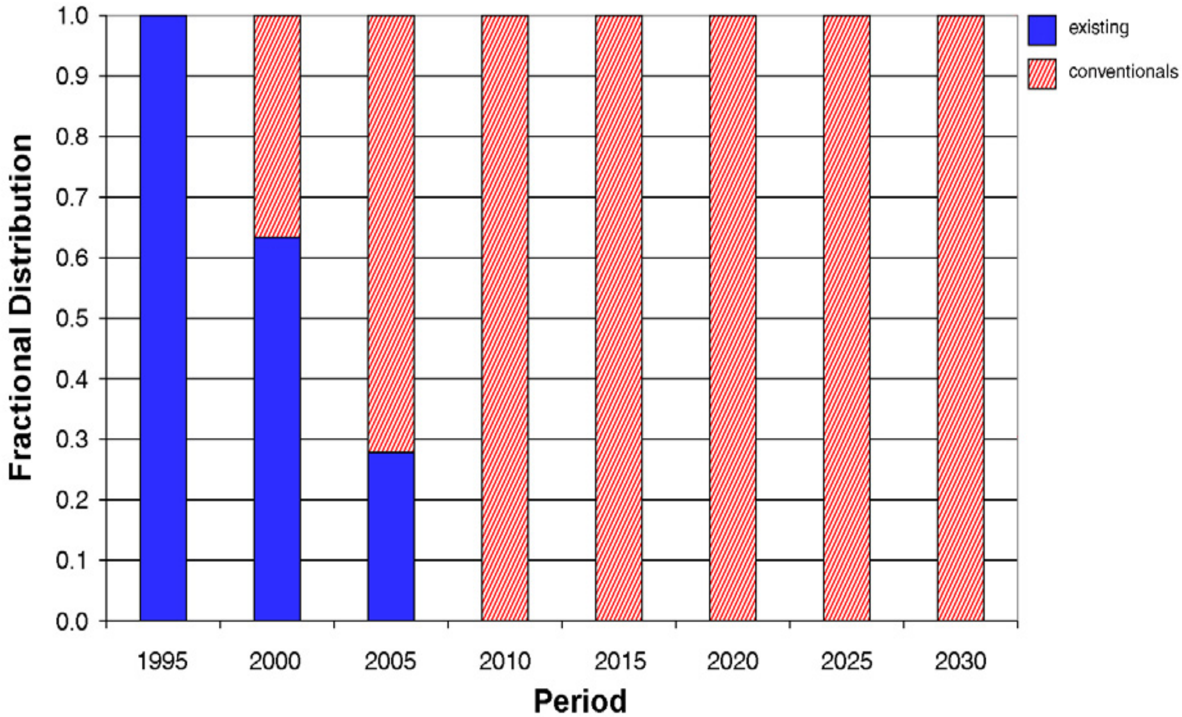

Figure 23. Technology Penetration per Period for CD Scenario.

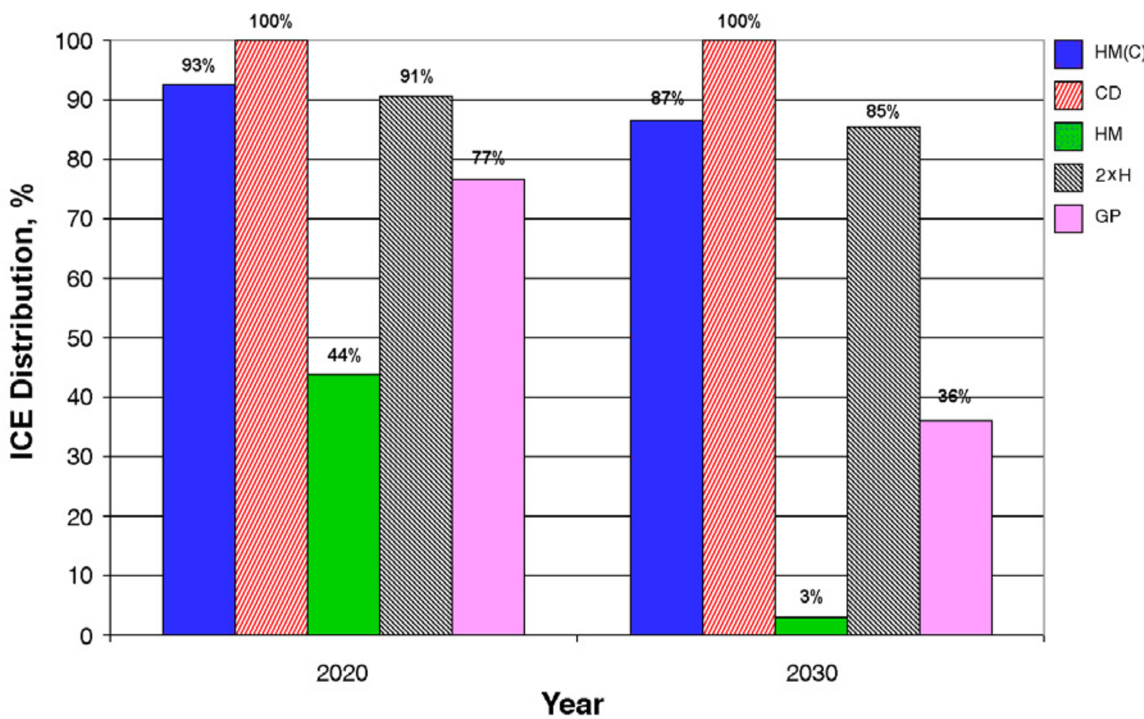

Figure 24. Comparison of Non-Hybrid Penetrations across EAU Scenarios at 2020 and 2030.

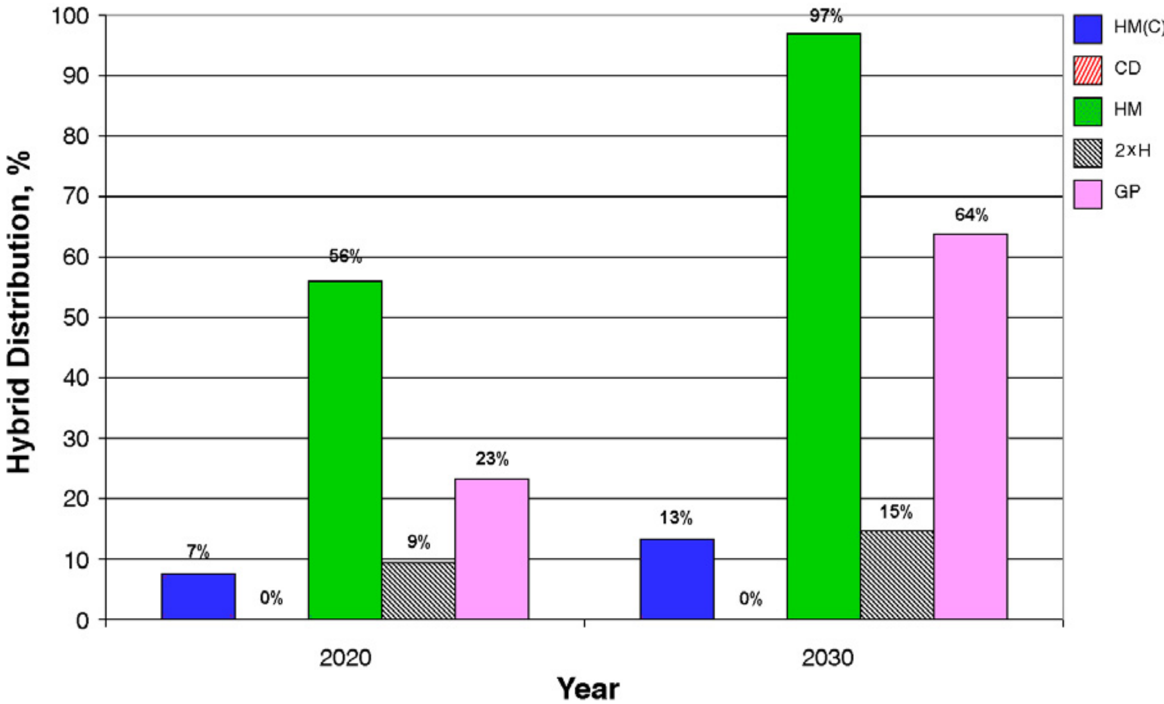

Figure 25. Comparison of Total Hybrid Penetrations across EAU Scenarios at 2020 and 2030.

The two HM(C) scenarios probe the extent to which relative investment costs determine hybrid penetration. Starting with hybrids, a 10 percent investment cost reduction on 2X vehicles during the 2000 and 2005 time periods—equivalent to today's hybrid vehicle tax credit—increases aggregate 2030 hybrid market share to nearly 28 percent, with all the growth coming in 2X vehicles at the expense of their advanced efficiency ICE counterparts (Figure 26). Likewise, a 16 percent increase in advanced efficiency ICE investment costs blocks their market entry and boosts hybrid penetration to 31 percent. Conventional ICE and advanced diesel vehicles meet the remaining transportation demand.

The remaining EAU scenarios expand the HM(C) analysis. The 2X Scenario (2XH), for instance, examines a technology path that excludes 3X hybrids. In this situation where the DOE's more optimistic technology development goals are not reached, hybrids achieve the same overall 2030 hybrid market share as HM(C), about 13 percent (Figure 20). The EAU Gas Price Scenario (GP), in contrast, shifts the 2X-3X balance and achieves a significant hybrid penetration—a 64 percent market share that favors 3X hybrids when the price of gasoline reaches $4.5/gallon (advanced mpg ICE vehicles meet the remaining demand; see

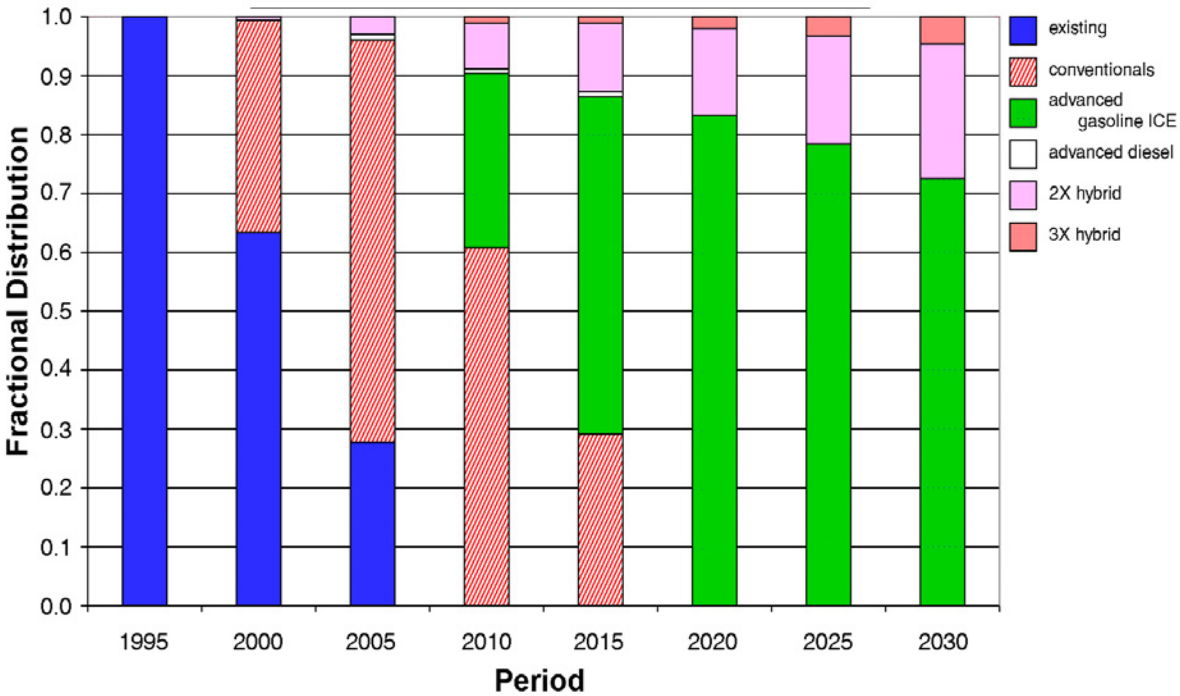

Figure 26. Technology Penetration in HM(C) Scenario with 10% Price Incentive for Hybrids.

Figure 21). The Hybrid Market Without Conventionals Scenario (HM) goes further; 3X hybrids capture nearly 83 percent of the transportation market when manufacturers phase out all ICE-powered vehicles, with 2X hybrids and advanced diesel-fueled vehicles meeting the remaining demand (Figure 22).

Advanced efficiency vehicles therefore remain competitive unless gas prices nearly triple (GP) or gasoline-electric hybrid engines become the new “conventional” power train (HM). Note that the EAU Conventionals Dominate Scenario (CD) postulated three situations under which ICE vehicles might entirely out-compete their hybrid equivalents: a higher hurdle rate on all non-conventional transportation technologies (including advanced efficiency ICE-powered vehicles), a sustained reduction in gas prices (to, say, $1.0/gallon), and a higher-than-expected [15 percent over HM(C)] hybrid investment cost. The CD scenario in Figure 23 captures the effects of the first situation, and Figures 27 and 28 illustrate the effects of the latter two situations.

Figure 29 compares gasoline consumption across the EAU scenarios and serves as the bridge between the technology paths illustrated previously and the corresponding emission profiles presented in Figures 30 through 33. In all scenarios except CD, gasoline

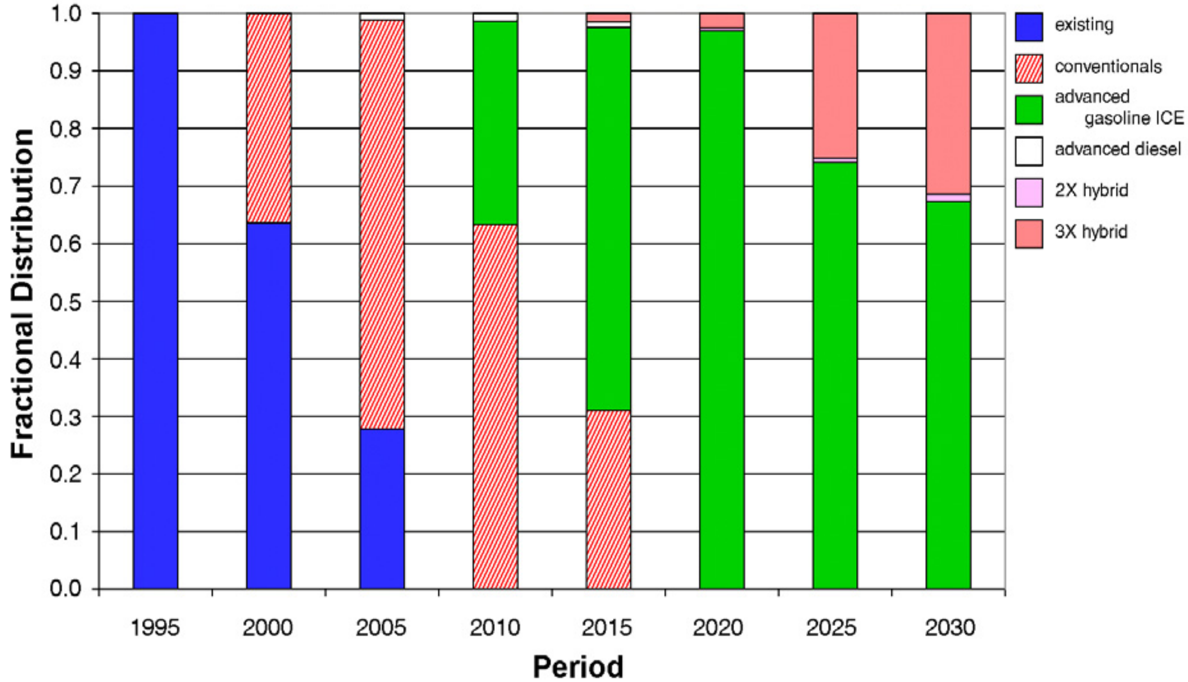

Figure 27. Technology Penetration in HM(C) Scenario with ($0.50/gal) Gas Price Reduction.

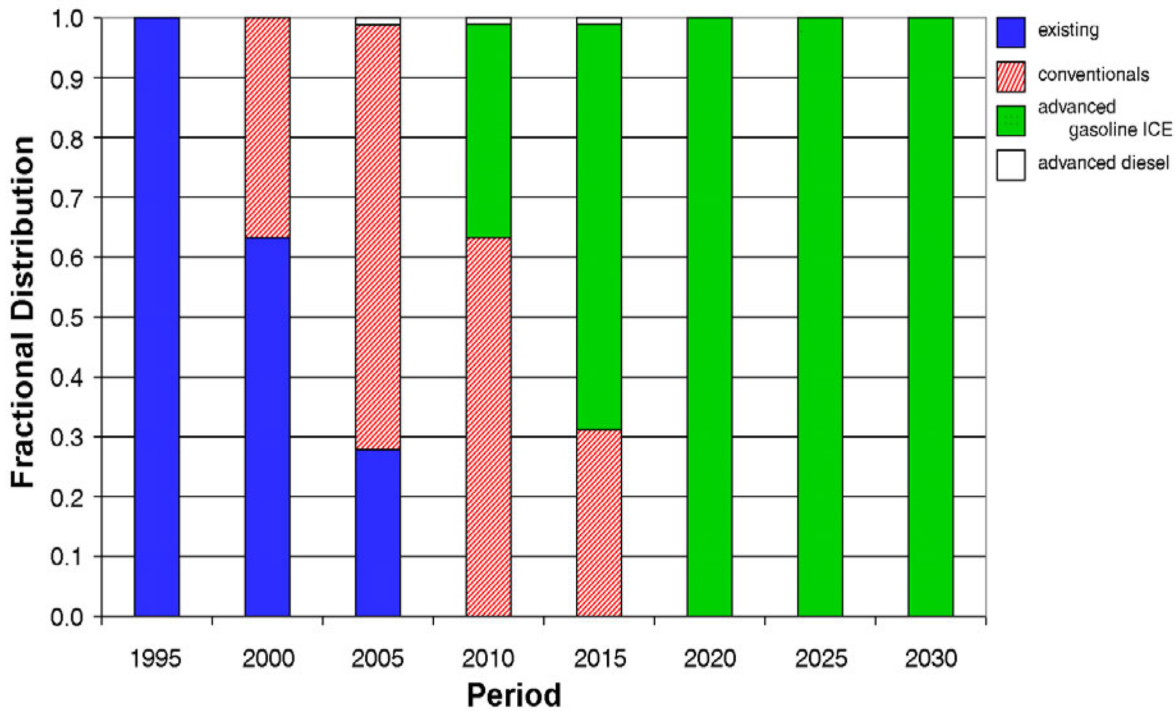

Figure 28. Technology Penetration in HM(C) Scenario with 15% Price Increase on Hybrids.

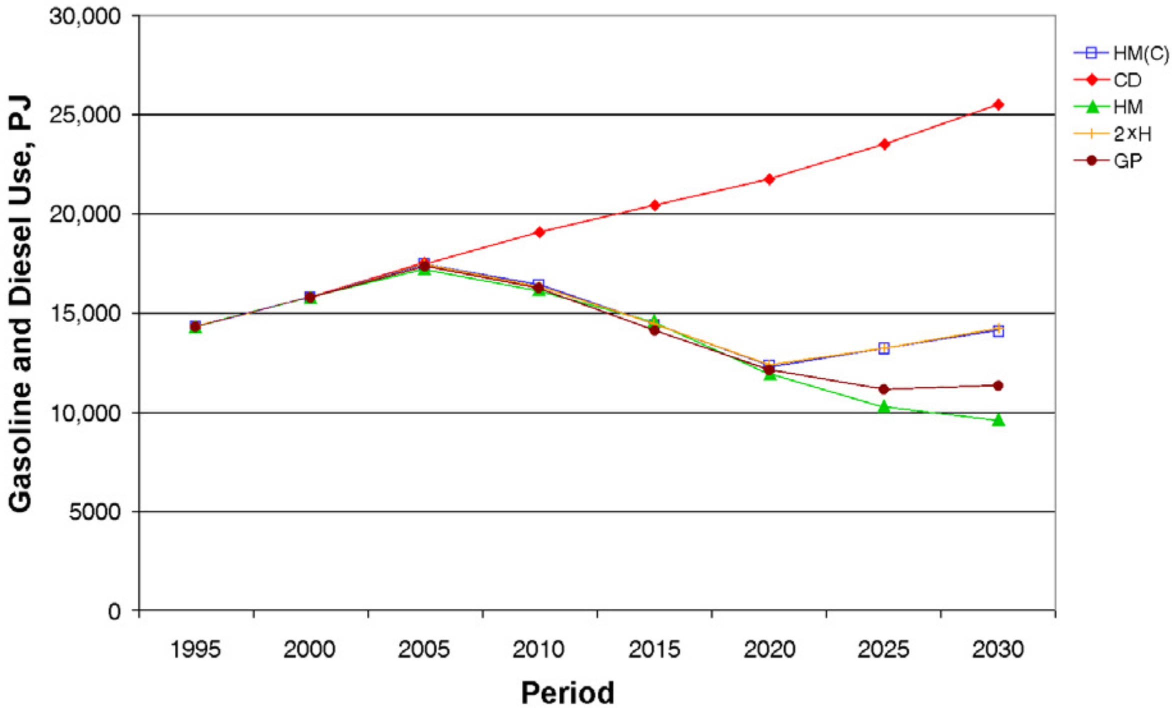

Figure 29. Per-period Gasoline and Diesel Consumption across EAU Scenarios.

consumption peaks relatively early (in the 2005 time frame) and then declines as a combination of more efficient advanced ICE vehicles and hybrids enters the market and the useful life of pre-2000 vintage vehicles ends. The decline is sustained for the scenarios with substantial 3X hybrid penetration (HM and GP); otherwise, gasoline consumption begins a modest upward trend after 2020 as the increase in transportation demand (miles traveled) overcomes the improvement in vehicle fleet efficiency in determining total fuel requirements. By 2030, transportation sector gasoline demand for the CD scenario is nearly 80 percent above the scenario with the second greatest fuel consumption (2XH) and is more than twice that of several others. Improvements in overall vehicle efficiency, achieved via diffusion of both advanced efficiency ICE and hybrid vehicles, therefore have a significant impact on resource requirements, with the magnitude of the reduction in gasoline consumption directly proportional to hybrid penetration.

The emission results paint a similar picture. Figures 30 through 33 compare PM_{10} (PM with aerodynamic diameter 10 μm or less), CO, NO_X, and VOC emissions (respectively) across scenarios. The figures express emissions for the 2030 time period relative to the CD scenario in which conventional ICE vehicles dominate the transportation market. In all cases, the all-hybrid HM scenario (83 percent high-efficiency 3X vehicles) achieves the

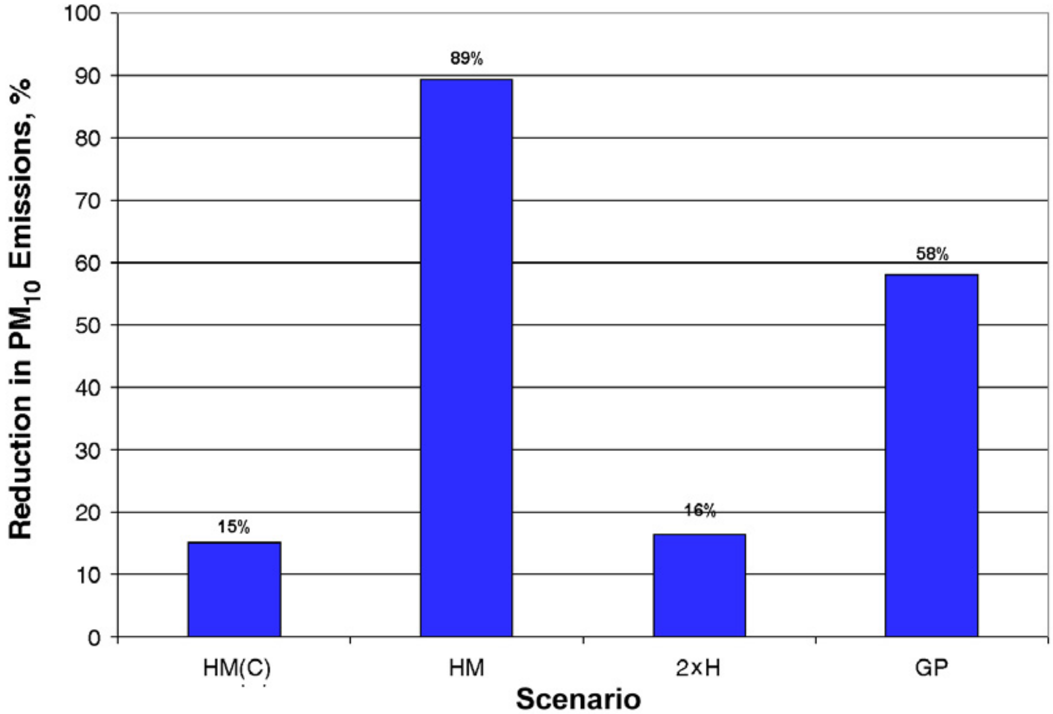

Figure 30. PM_{10} Emission Reductions in 2030 Relative to the CD Scenario (20 thousand tons PM_{10}/yr).

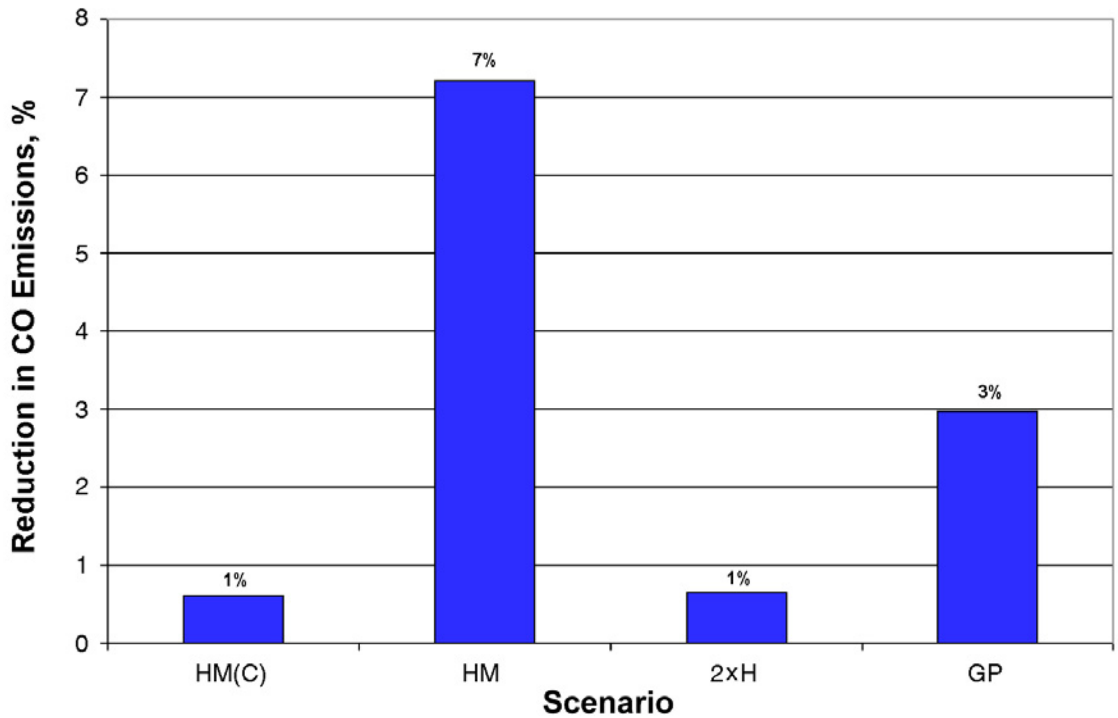

Figure 31. CO Emission Reductions in 2030 Relative to the CD Scenario (7590 thousand tons CO/yr).

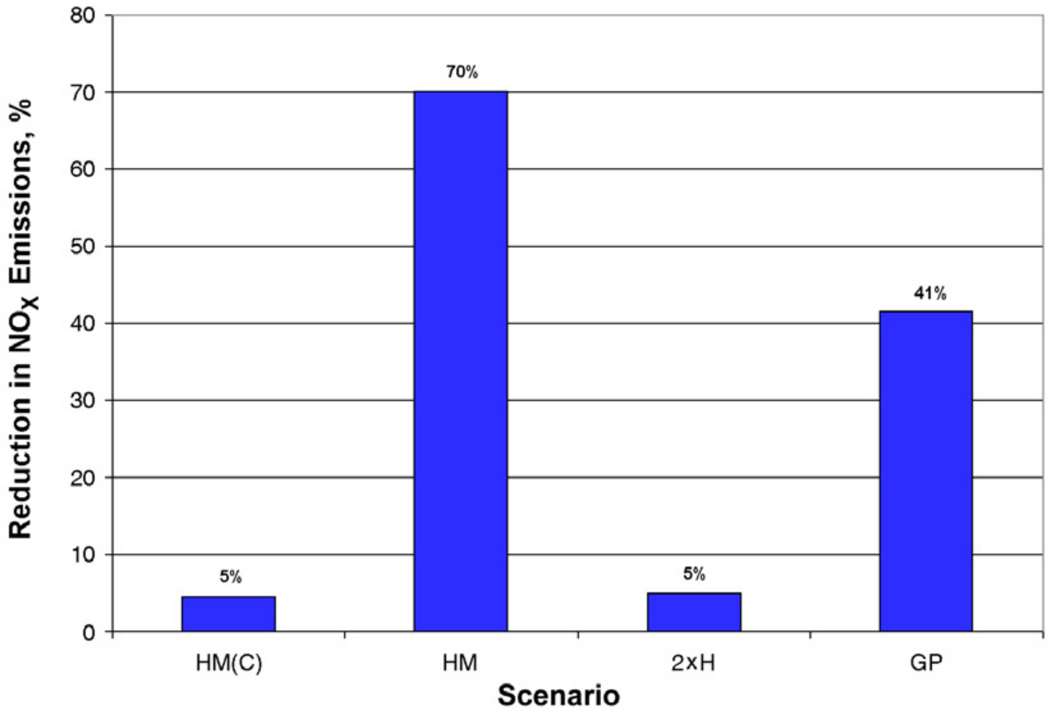

Figure 32. **NO_X Emission Reductions Relative to CD Scenario (300 thousand tons NO_X/yr).**

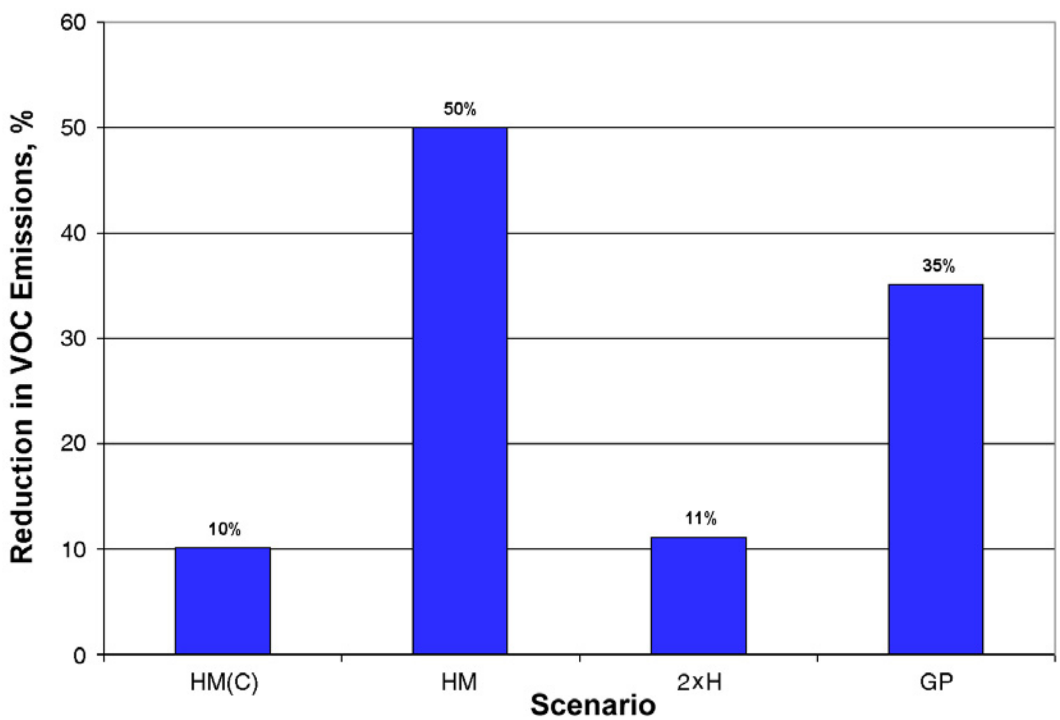

Figure 33. **VOC Emission Reductions in 2030 Relative to CD Scenario (230 thousand tons VOC/yr).**

largest relative emission reduction, followed by GP, 2XH, and the moderate hybrid HM(C). In short, the greater the hybrid market penetration, the greater the emissions reduction in 2030 relative to a conventional ICE-only world. Maximum differences range from nearly 90 percent for PM_{10} to 17 percent for CO, with reductions of 70 and 50 percent, respectively, for NO_X and VOCs.

The Section 6.3 provides further discussion of the EAU results in its comparison with the EPHE scenario findings. The results from the latter, which represent the TACT's first steps toward its long-term goal of a comprehensive hydrogen economy analysis, are presented next.

6.2 EPHE Scenario Outcomes

The EPHE scenarios add a H_2 fuel infrastructure and H_2 FCVs to the EAU framework. The EPHE storylines—especially the Hydrogen Market (H2M) and Optimistic Hydrogen (H2O) scenarios—first ask how these additions displace hybrid and advanced efficiency ICE vehicles and ask then how these shifts in technology market penetration impact transportation sector emissions. Beyond this comparison, the EPHE Hydrogen Forcing Scenarios (H2F) look at how the need to meet a given H_2 vehicle market share affects the means of supplying H_2 fuel. This section addresses these questions, while the following section draws more general conclusions from a comparison of the EAU and EPHE scenarios.

Figures 34 and 35 show how the H2M and H2O assumptions affect vehicle technology market share in meeting actual per-period transportation demand (in billion VMT); Figures 36 and 37, respectively, express the same data on a percentage basis. By 2030, H_2 FCVs in the H2M scenario achieve a modest (9.3 percent) market penetration; the more optimistic H2O assumptions increase this value slightly (to 13.7 percent). Advanced efficiency ICE vehicles meet better than 80 percent of transportation demand for both EPHE scenarios, whereas the total hybrid market penetration remains below 10 percent. Thus the introduction of H_2 FCVs takes market share primarily from hybrids. An 8 percent increase in all H_2 vehicle investment costs is sufficient to drive FCVs out of the market, reproducing the EAU HM(C) (Hybrid Market with Conventionals) scenario.

Gasoline consumption across EPHE H2M and H2O scenarios mimics that of the EAU storylines (Figure 38). Fuel use peaks early and declines for several model periods before leveling off after2020. Once H_2 FCVs enter the market, they capture a substantial part of the growth in transportation demand over subsequent periods, while the market share of advanced efficiency ICE vehicles plateaus. Gasoline consumption changes accordingly.

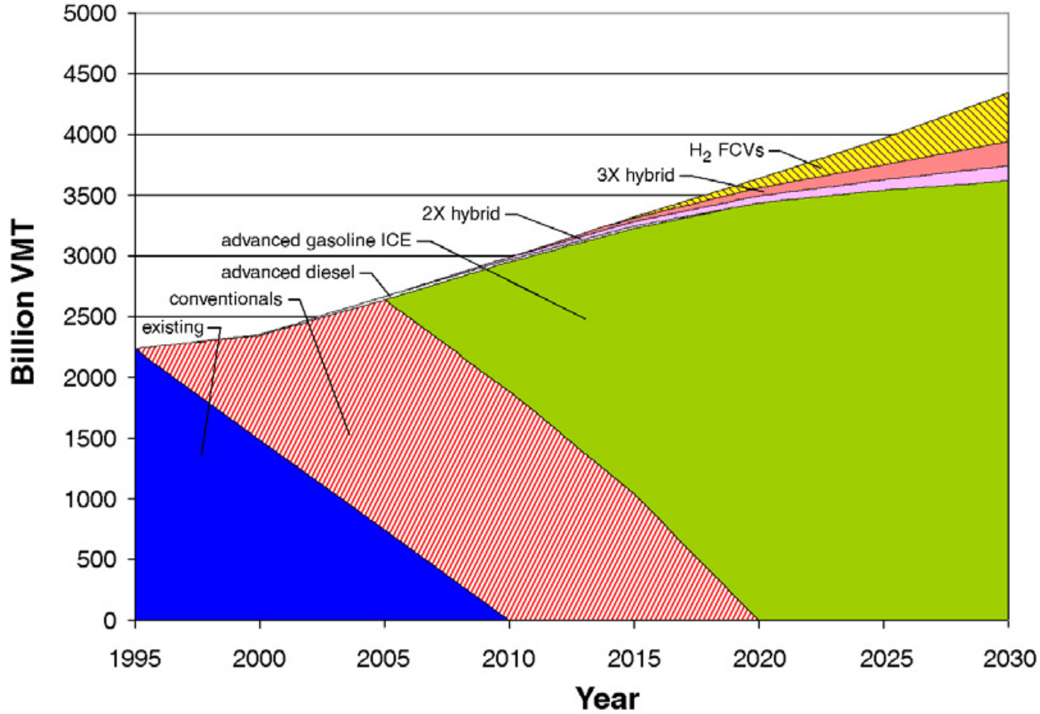

Figure 34. Per-period VMT for each Technology in the H2M Scenario.

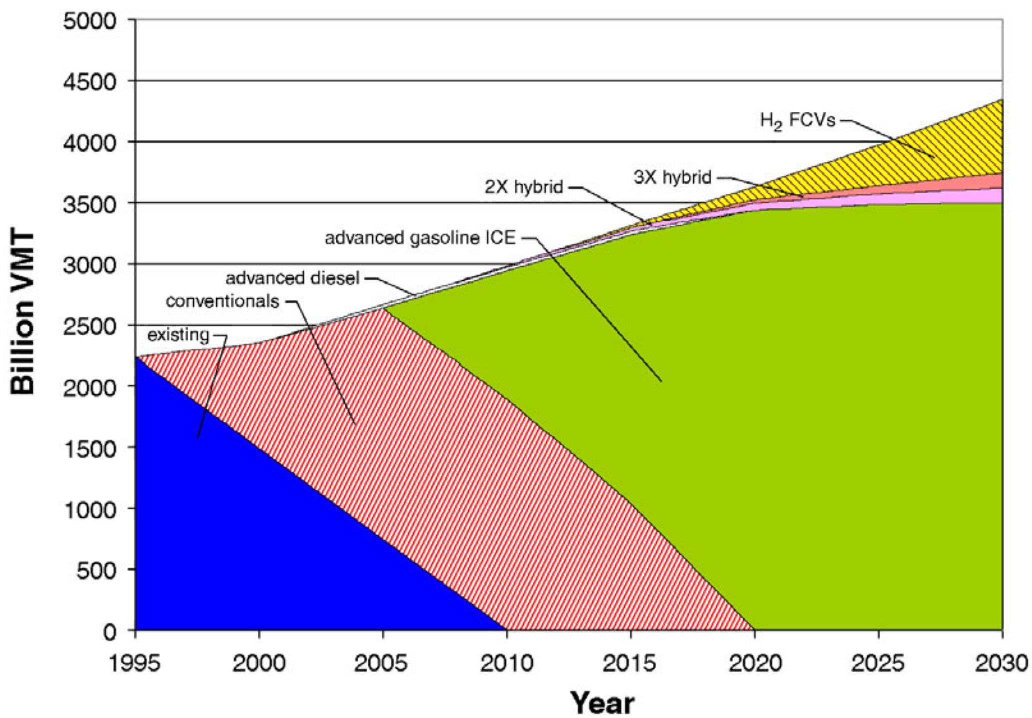

Figure 35. Per-period VMT for each Technology in the H2O Scenario.

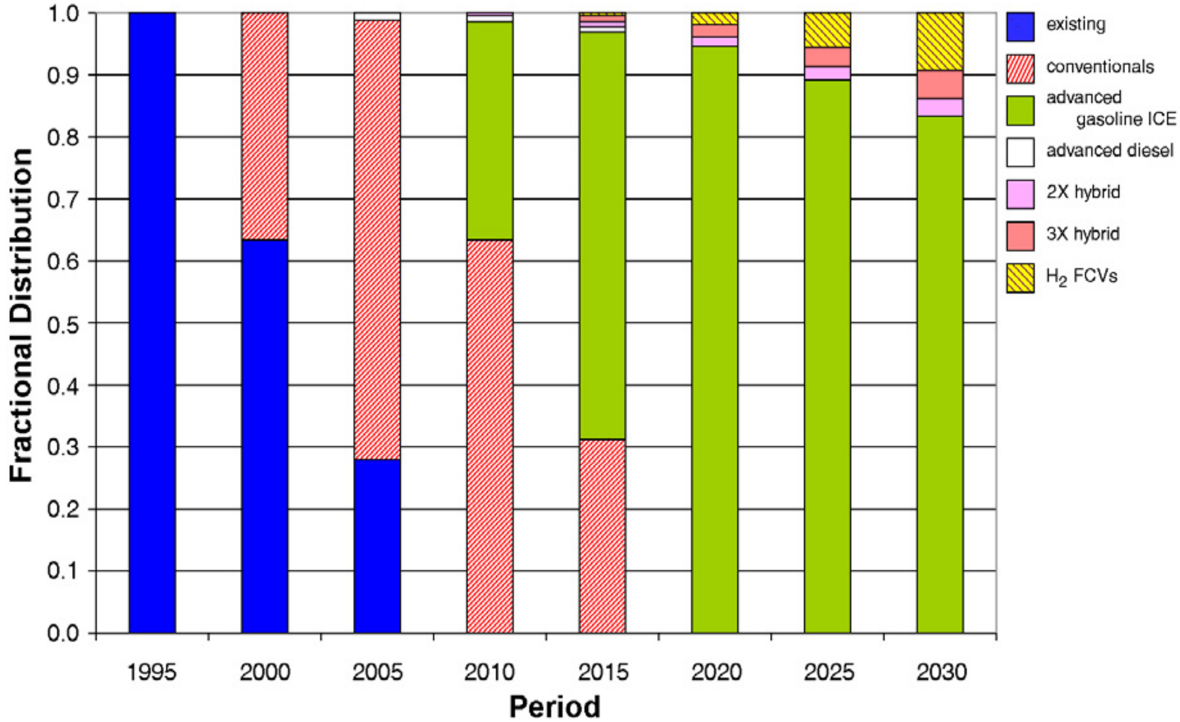

Figure 36. Technology Penetration per Period for H2M Scenario.

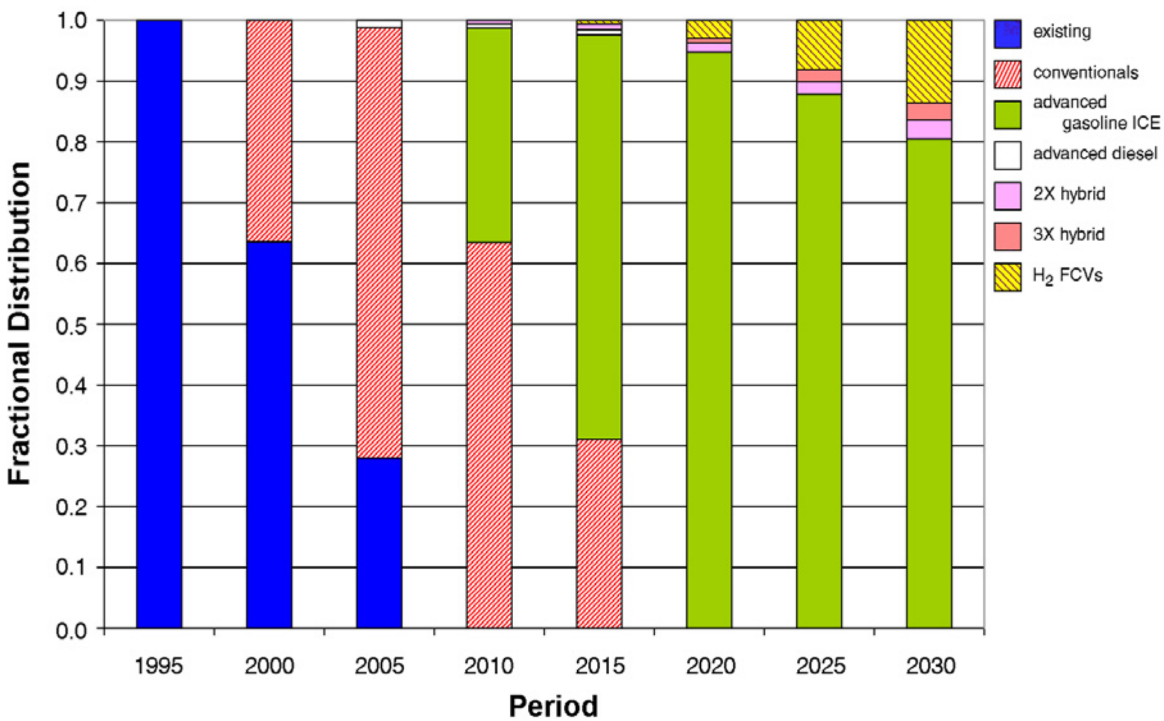

Figure 37. Technology Penetration per Period for H2O Scenario.

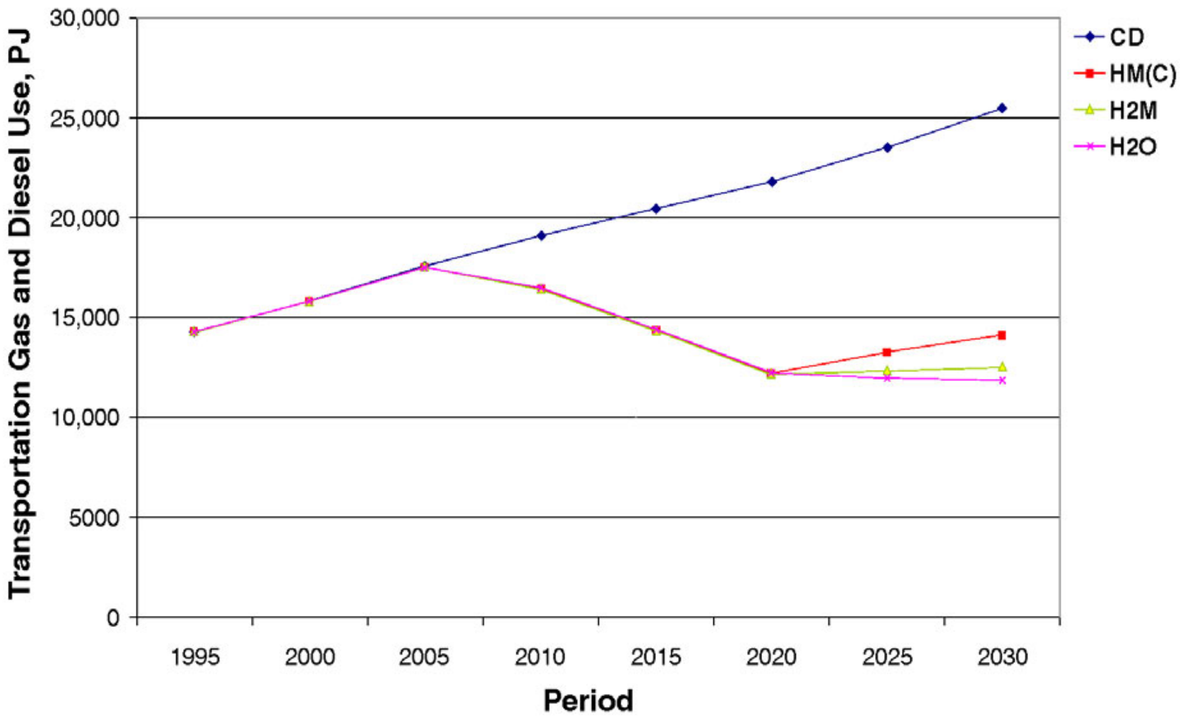

Figure 38. Per-period Gasoline and Fuel Use for EPHE Scenarios.

Figure 39 expresses the H2M and H2O emissions for 2030 relative to the HM(C) values. The modest displacement of gasoline-fueled vehicles (ICE and hybrid) by their H_2 fuel cell counterparts yields relative emissions reductions that range between 5 percent for both PM_{10} and NO_X, to 10 percent for CO and 16 percent for VOCs, given the H2M assumptions. The more optimistic H2O assumptions increase these reductions to 8 (PM_{10} and NO_X), 14 (CO) and 24 percent (VOCs). Again, these numbers reflect decreases in transportation sector (i.e., tailpipe) emissions, and are therefore a function of the displacement of one vehicle technology (or fuel) by another. Future TACT work will examine the lifecycle emissions associated with the full H_2 fuel cycle, particularly those that occur "upstream" with H_2 production. Significant H_2 consumption might also indirectly affect emissions outside the H_2 fuel chain. Sufficient demand for H_2 would affect the price—and, therefore, consumption—of natural gas and electricity across the economy. With completion of the electric sector database, MARKAL will allow TACT to examine the associated impacts on emissions.

The EPHE scenarios as currently modeled, however, provide an initial look at how H_2 fuel might be supplied. All H2M and nearly all H2O hydrogen, for instance, is produced at local refueling stations by steam methane reforming (electrolysis at the refueling station provides

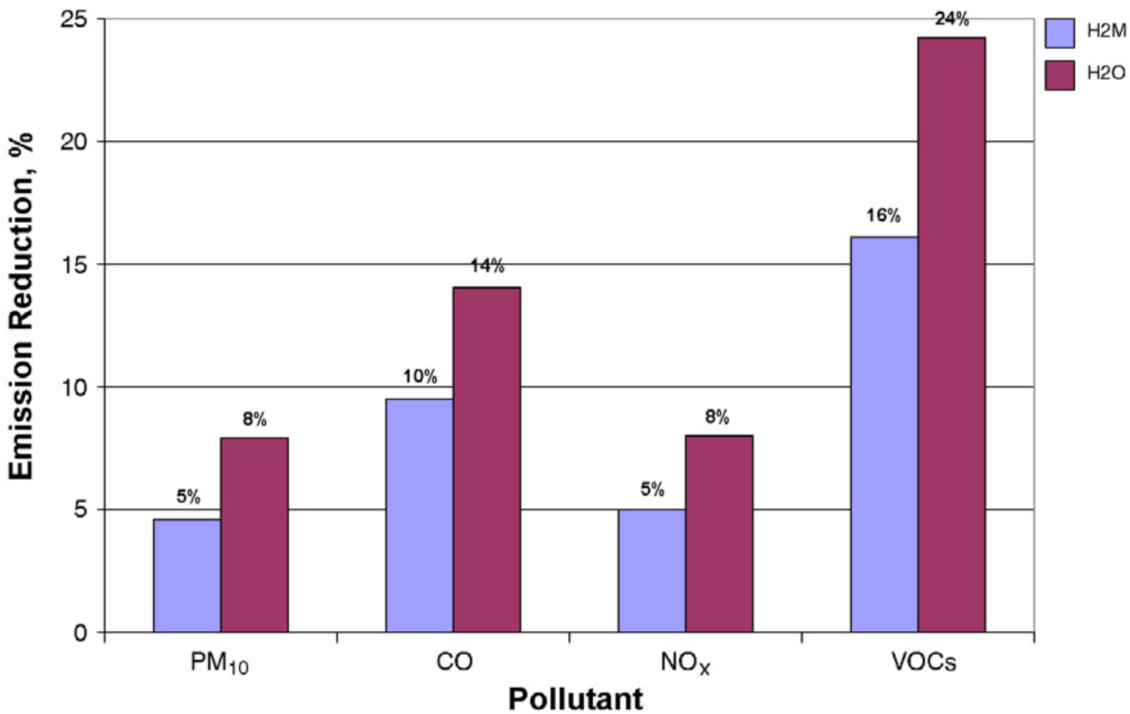

Figure 39. Emissions Reductions for EPHE Scenarios Relative to HM(C) Scenario.

nearly 10 percent of the H2O scenario H_2). Given the EPHE H2M assumptions, forcing a minimum H_2 vehicle market share (up to 50 percent by 2030) does not affect the preference for steam methane reforming. This technological preference, however, does divert an increasing share of natural gas into H_2 production as the market share of H_2 FCVs grows. The EPHE H2M Scenario, for instance, requires nearly 4 percent of the natural gas consumed economy-wide in 2030 in order to achieve a 9 percent vehicle penetration, whereas a forced 50 percent market share requires over 15 percent of the total gas consumed to meet its H_2 needs. Subsequent TACT analysis will explore the economic implications of this diversion.

The EPHE forcing scenarios also illustrate how gasoline consumption and emissions vary with market entry and penetration of H_2 FCVs. Figure 40 compares 2030 gasoline consumption across the five H_2 FCV forcing runs. The largest decrease from a conventional ICE-only world comes with the entry of hybrids as shown in Figure 29. Comparing Figures 38 and 40 shows that the adoption of H_2 FCVs yields further reductions in gasoline consumption only when their market share begins to exceed 20 percent. Emissions relative to the EAU CD scenario vary inversely with adoption of hydrogen FCVs, and production of PM_{10}, CO, NO_X, and VOCs decreases to half of EAU CD levels when forced penetration reaches 50 percent (Figure 41).

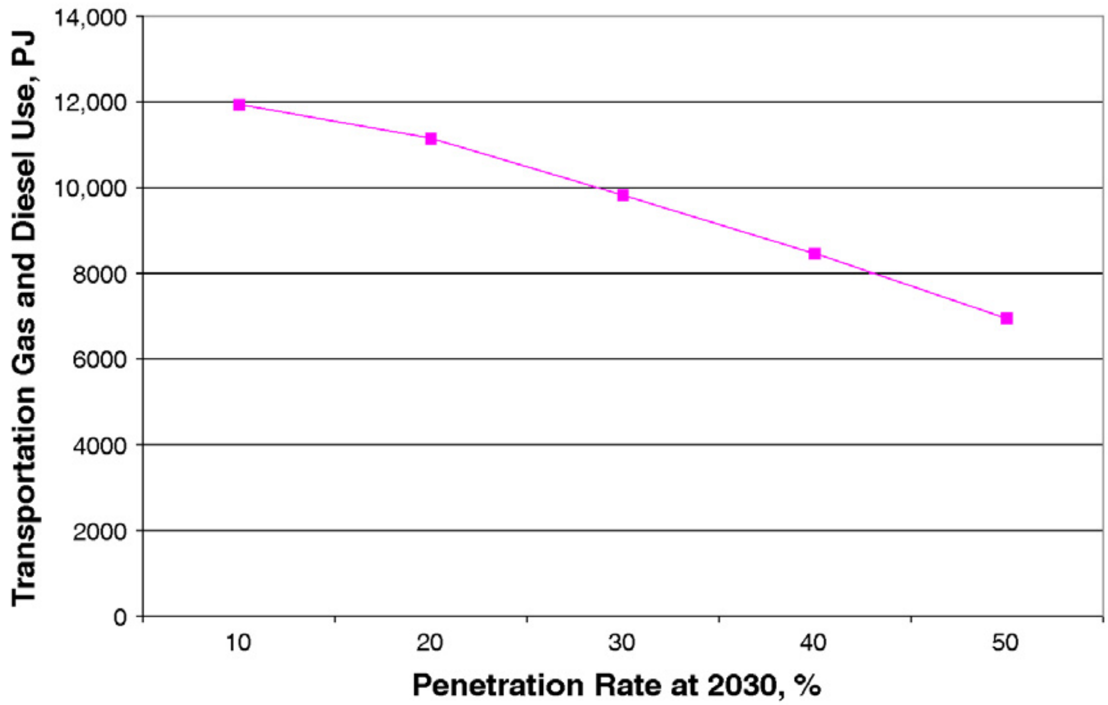

Figure 40. Gasoline and Diesel Consumption in 2030 for the H2F Scenarios.

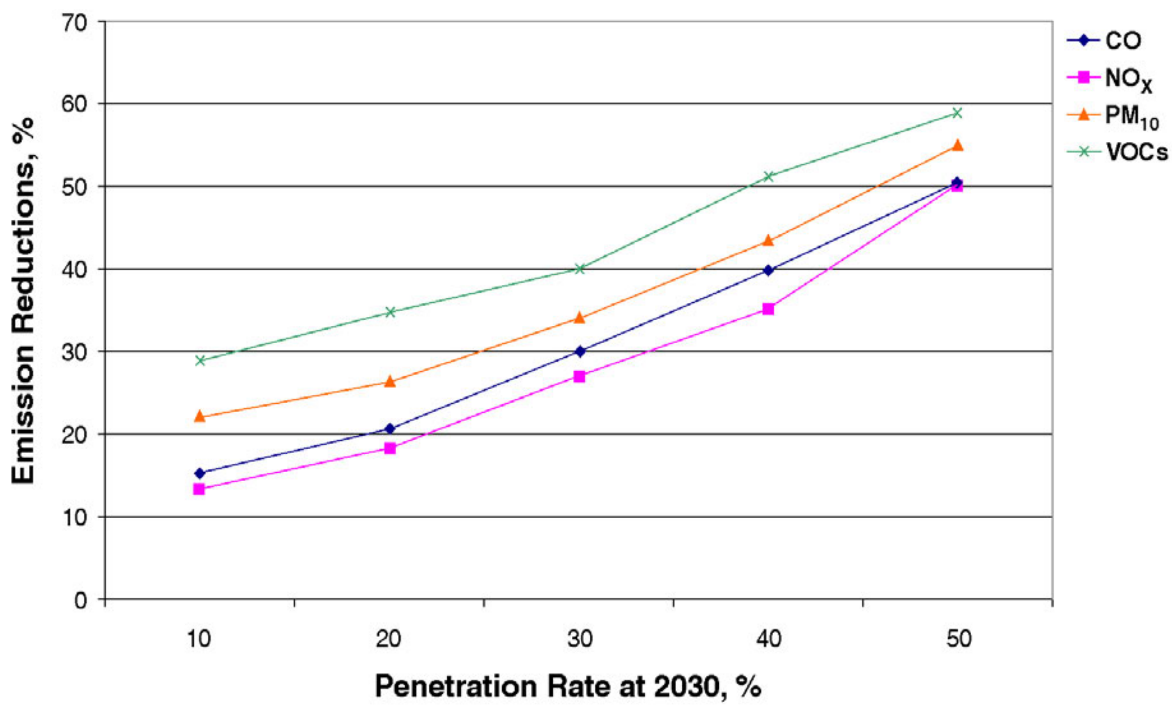

Figure 41. Emission Reductions (%) in 2030 for the H2F Scenarios.

Apart from the macroeconomic issues hinted at here, future EPHE scenario work will examine the transition to a hydrogen economy. Gasoline fuel cells, for instance, would likely play an important role in the early diffusion of transportation fuel cell technology. The complete MARKAL transportation database will provide this more comprehensive picture of the route from the present to various transportation futures.

6.3 Comparison of EAU and EPHE

The EAU and EPHE scenario analyses tell an incremental story about the diffusion of alternatives to conventional ICE vehicles and the resulting impact on transportation sector emissions. Variations in assumptions about factors thought likely to drive future preferences for conventional and advanced efficiency ICE vehicles versus their hybrid counterparts yielded the EAU scenarios. The EPHE storylines built on this analysis by introducing a H_2 fuel infrastructure and hydrogen FCVs.

As the previous section noted, advanced efficiency ICE vehicles continue to meet at least four-fifths of transportation demand in 2030 if cost and performance numbers for the technologies included here fall near their assumed values (given, as well, the larger set of assumptions embedded in the MARKAL modeling framework). These values are derived from the recent literature and, therefore, reflect current thinking. MARKAL, in turn, provides a consistent means of determining the consequences of these assumptions whuch, in this case, indicate that, all other things being equal, gasoline-electric hybrid and hydrogen FCVs do not achieve more than a combined 20 percent market share before 2030. Situations such as a significant increase in gasoline prices (the EAU GP scenario) affects these conclusions, and it is not hard to imagine technological, economic, and political factors—some that necessarily fall outside of this modeling framework—that might easily change the outcome. Hence, the results presented here should not be taken as predictions about an unknowable future.

The market penetration of hybrid and H_2 fuel cell technologies is constrained in both EAU and EPHE scenarios by a combination of high investment costs and rate of growth constraints. Although the latter may seem to be an artifact of the model, the growth constraints reflect the gradual nature of historical technology diffusion and recognize that supporting infrastructure must evolve in tandem with end-use technology. As captured here, more radical transportation infrastructure change includes the development of a system to provide H_2 fuel, but also recognizes the need for vehicle manufacturers to commit to a new technology and retool their assembly lines.

Incorporating learning and economy-of-scale effects in the model might yield a more favorable outcome for hybrids and H_2 fuel cells as investment costs and efficiencies would likely improve with market penetration, which would in turn lead to even greater penetration in subsequent time periods. The EAU and EPHE results described above are, therefore, conservative in the sense that they do not capture these dynamics endogenously (i.e., MARKAL takes all per-period costs and efficiencies as input assumptions and cannot change their values to reflect growing investment). MARKAL-ETL (Endogenous Technology Learning) incorporates technological learning in an extended version of the basic MARKAL model and may be adopted for future TACT analysis.

Notable across the scenarios, however, is a tendency to select higher efficiency technologies in the transportation sector. In most scenarios, these higher efficiency vehicles are predominantly advanced efficiency ICE vehicles, with hybrids and H_2 fuel cells achieving a small but stable market share by 2030. In these preliminary emissions modeling results, these selections have a significant impact on transportation sector emissions. Figures 42 through 45 show emission reductions for the EAU and EHPE scenarios, all expressed relative to the EAU conventional ICE-only (CD) scenario. The greatest reductions are seen in PM_{10}, with significant changes in VOCs and, for a couple of scenarios in particular, in NO_X as well. The

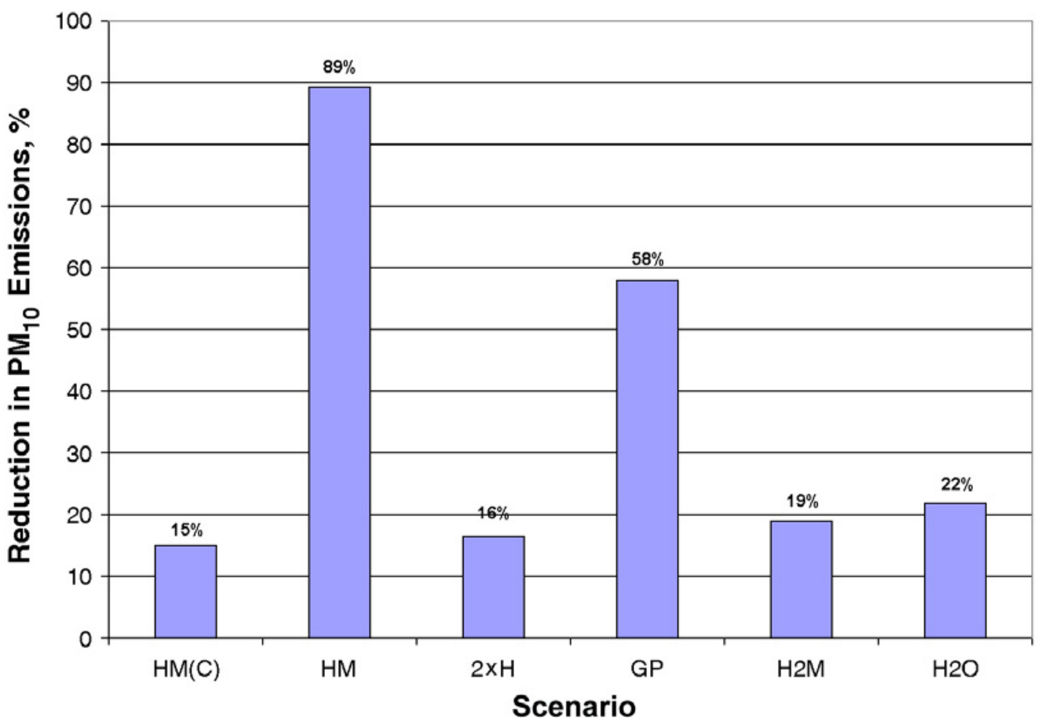

Figure 42. PM_{10} Reductions in 2030 for EAU and EPHE Scenarios Relative to CD Scenario.

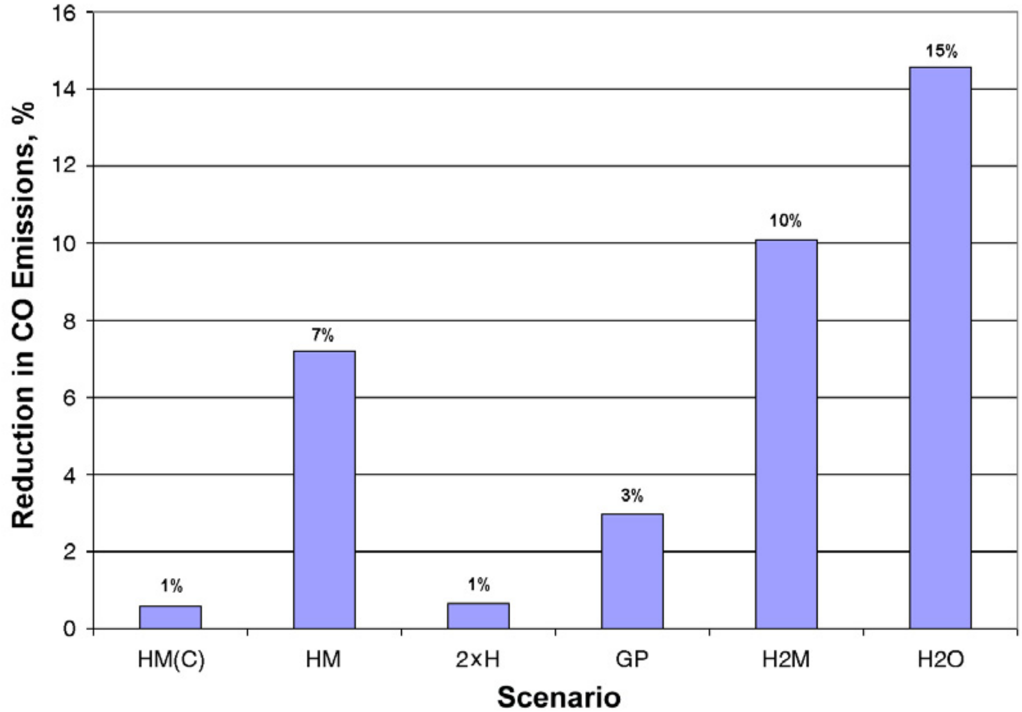

Figure 43. CO Reductions in 2030 for EAU and EPHE Scenarios Relative to CD Scenario.

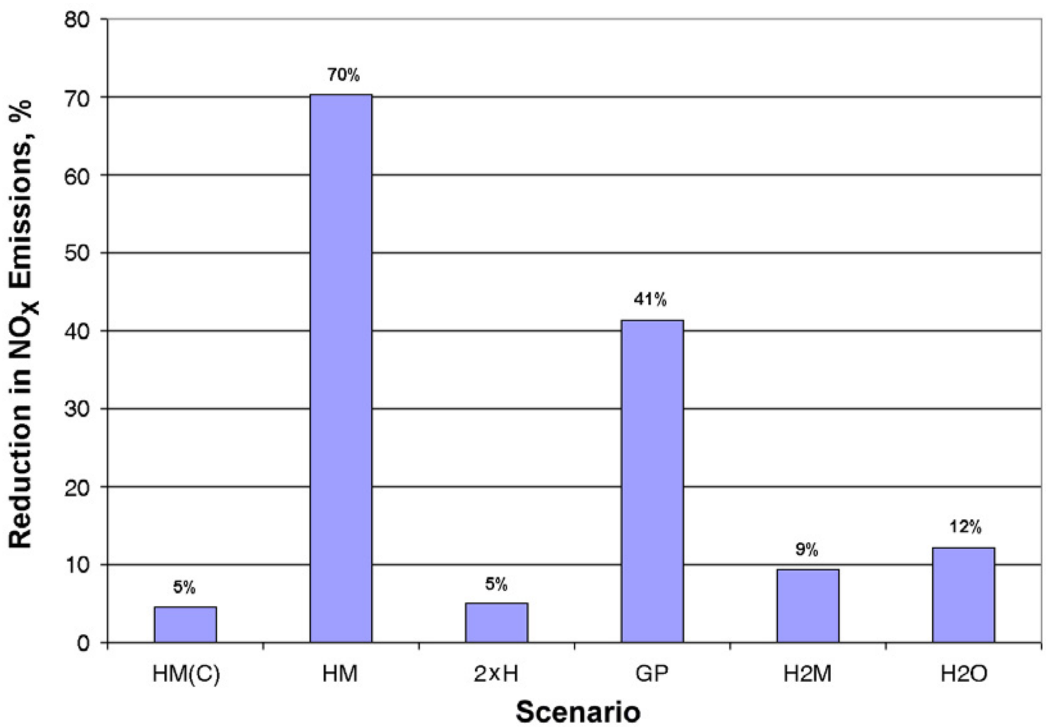

Figure 44. NO_X Reductions in 2030 for EAU and EPHE Scenarios Relative to CD Scenario.

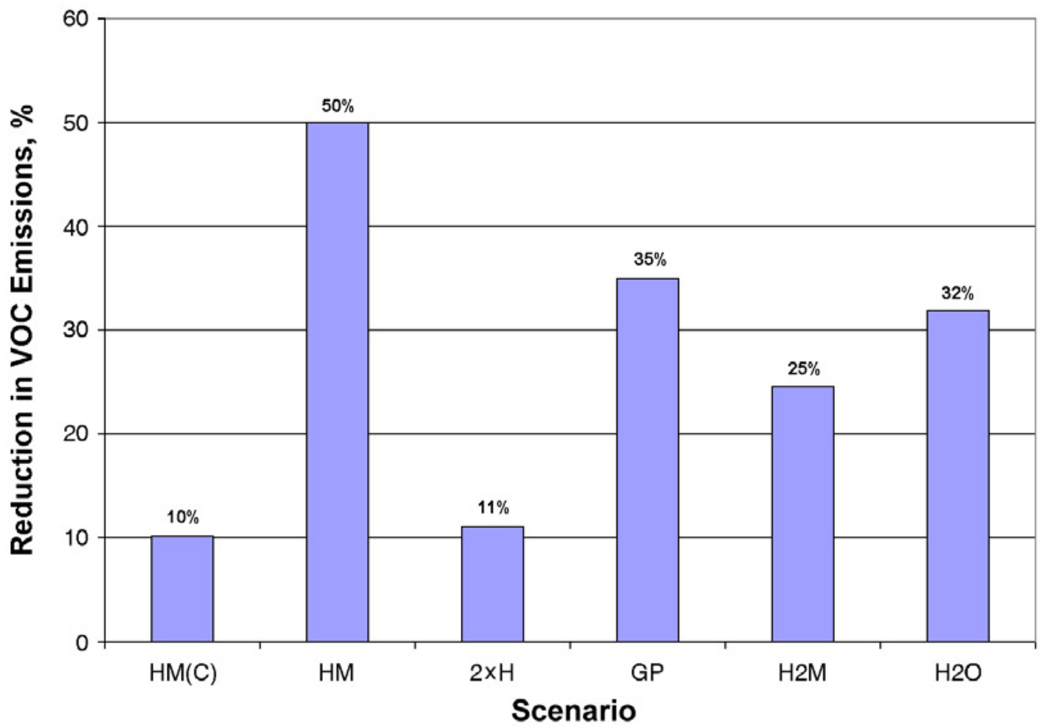

Figure 45. VOC Reductions in 2030 for EAU and EPHE Scenarios Relative to CD Scenario.

two hybrid-heavy EAU scenarios (HM and GP) achieve the largest relative decreases in PM_{10}, NO_X, and VOCs. The availability of hydrogen FCVs, on the other hand, yields the largest CO reductions relative to a world constrained to conventional ICE vehicles. A more thorough and sophisticated emissions analysis will be necessary to determine the likely extent and distribution of such reductions in these and other scenarios.

Section 7
Future Work

This report has described the process TACT will use to evaluate technology scenarios for their impact on future air emissions. Example results are provided for personal vehicles, an important component of the transportation sector.

The purpose of this section is to describe the next steps toward the goal of providing comprehensive energy system assessments from future technology changes in the transportation and electricity generation sectors. Anticipated steps are described below, including continued database development and extension to 2050, documentation, and release; improvements to the representation of the transportation and electricity sectors; evaluation of approaches for incorporating economic interactions; the development of a set of alternative technology futures, sensitivity and uncertainty analysis; and integration with the ORD Air Quality Assessment.

7.1 Database Development

One of the primary products of this work will be the public release of the U.S. Reference Energy System database. The final development activities for this release involve implementing the refinements to the industrial sector (as discussed in Section 2), completion of the emission factor component of the database, and development of supporting documentation, including documentation of the calibration process. Each of these activities is on-going. The database will be extended to 2050, in order to support TACT's analyses for the ORD Air Quality Assessment and will be updated to AEO 2004. The database as a whole will also be reviewed by MARKAL modelers. (To this point, review has been on a sector basis, by sector-appropriate energy experts who are not necessarily MARKAL users.) The database and supporting documentation are expected to be ready for release in the fall of 2004.

7.2 Expansion of Future Technologies in the Transportation Sector

As discussed in Sections 3 through 6, significant work has been done to characterize personal vehicle fuels and technologies. Additional work in this area will be to include biofuels such as methanol, ethanol, and biodiesel. Conversion processes for forming biofuels are presently being investigated, as are the associated transportation technologies, such as methanol- powered FCVs. Additional work outside the personal vehicle subsector may include analyses of future technologies and fuels for freight and mass transit.

7.3 Expansion of Future Technologies in the Electricity Generation Sector

As core database and scenario work on the transportation sector begins to near completion, the TACT team will shift its focus to electric power generation. Modeling of the U.S. electric sector will continue to follow the same pattern of activities that TACT has pursued with transportation. Although much of the electric sector portion of the MARKAL database is in place, emission coefficients for combustion technologies, for instance, must be added and an approximate calibration to AEO numbers accomplished. Following completion of the database, TACT electric power specialists—in consultation with other knowledgeable individuals within and outside of the EPA—will assemble a series of advanced technology scenarios akin to the transportation EAU and EPHE storylines.

A scenario-development philosophy similar to that described in this report will guide the electric sector work. Evolution as Usual storylines examining gradual improvements in coal- and natural gas-fired generators, as well as wind, solar, nuclear, and other contemporary non-fossil energy sources will be constructed. These scenarios will be compared to electric sector futures that represent a more radical shift from an evolution of the current U.S. power generating infrastructure. Technology scenarios that fall into the latter category include CO_2 capture and sequestration, which promises to be an important route to a more comprehensive hydrogen economy. As envisioned by the DOE's FutureGen initiative, H_2 would be produced via coal gasification or natural gas reforming at centralized plants, with the resulting CO_2 injected into an underground geological formation. The H_2 would then be available for use in turbines for electric power generation, or it could be sold for transportation use. Further electric sector scenarios might focus on more radical improvements in solar technologies and even the transition to a distributed power generating infrastructure (using, for instance, microturbines or fuel cells) provides further scenario options. A complete MARKAL model will allow an integrated lifecycle analysis of both transportation and electric sector technologies, one that will trace the implications of different scenarios along the chain of energy technologies from resource extraction, through processing and transformation to end-use.

7.4 Evaluating Approaches for Incorporating Economic and Learning Effects

Energy and vehicle demands are currently determined exogenously from MARKAL. Therefore, changes in energy prices is not currently captured although they would undoubtedly have an effect on these demands. Several approaches for capturing elasticity in demand are available. One such approach is to use a version of MARKAL called MARKAL-Elastic Demand. This model would allow energy service demands to be sensitive to price changes through price elasticities. Another potential approach would be to link MARKAL to an economic model. For example, a version of MARKAL called MARKAL-MACRO has been linked to a macro-economic model, allowing the effects of energy prices on economic growth and energy demand to be characterized. Alternatives to this approach include linking MARKAL with other economic models, such as Regional Economic Models, Inc. (REMI) or EPA's Economics Model for Environmental Policy Analysis (EMPAX).

Likewise, the present TACT MARKAL model takes all technology cost and efficiency parameters as fixed input assumptions that do not change with market share. The results discussed in this report, therefore, do not reflect the cost and performance improvements that come with the widespread adoption of a new technology. MARKAL-ETL (Endogenous Technology Learning), however, extends the base model to capture learning dynamics and economy-of-scale effects and may be adopted for future TACT analysis. The practicality, advantages, and disadvantages of each of these approaches will be explored.

7.5 Scenario Development and Analysis

Once the extension of the database to 2050 is completed and the database finalized, additional scenario runs will be performed in the transportation sector. From these scenarios, several storylines will be chosen in consultation with other research groups participating in the ORD Air Quality Assessment. Then the transportation futures (both technology options and penetrations) from these storylines will be provided for the next phase of the air quality work.

The TACT team will perform additional investigations on these scenarios analyzing the cost implications of technology choices. Several papers and presentations are anticipated from this work. Some of the hydrogen work will be provided to DOE's Hydrogen Analysis (H2A) workgroup. This group consists of members from national labs, universities, federal agencies and stakeholders with its mission to "Improve the transparency and consistency of approach to analysis, improve the understanding of the differences among analyses, and seek better validation from industry."

7.5.1 Generation of alternative future scenarios

MARKAL selects control technologies based on least cost. Thus, the MARKAL results are a prediction of the most inexpensive approach that could be taken (based on assumptions, etc.), but do not necessarily predict what will occur. Since corporations and consumers tend to act in such a way to reduce costs to themselves, it can be argued that the MARKAL results will identify tendencies. For the Air Quality Assessment, however, the goal will be to predict and characterize the ramifications on air quality of alternative technological futures. This implies that the model will be used to predict possible futures, a task for which the traditional use of least-cost optimization is not well suited.

An alternative approach is to modify MARKAL to perform a variant of least cost optimization called Modeling to Generate Alternatives, or MGA. MGA techniques provide an efficient means to develop a small set of distinctively different, yet reasonable, solutions to an optimization problem. In the context of MARKAL modeling, these alternatives can represent alternative technological futures.

In order to carry out a MGA analysis, the least cost solution is first identified. Next, the MARKAL objective function is modified to maximize the difference from the least cost solution, and a bound is placed on cost (e.g., 10 percent greater than the least cost). The model is then used to identify an alternative solution. The process is repeated, with the new objective being to maximize the difference from both the least cost and first alternative. Additional alternatives can be generated until a sufficient number have been identified or until no additional alternatives sufficiently different from the solutions already identified can be generated.

An advantage of MGA approaches is that they represent only incremental modifications to the original model formulation. Further, the similarity or difference among the alternatives can provide valuable information not available from only a least-cost solution. For example, if all of the alternatives that meet future air quality constraints involve the adoption of a hydrogen infrastructure, this suggests that such an infrastructure may be necessary to achieve the desired results. If, in contrast, a variety of very different solutions meet the air quality constraint, this suggests much more flexibility.

7.5.2 Sensitivity analysis

Given the set of plausible technological futures, an important next step will be to conduct a sensitivity analysis. Sensitivity analyses are useful in understanding how individual inputs and assumptions affect model results. For example, a sensitivity analysis may suggest that the effect of a parameter such as gasoline prices at the pump has a much greater impact on a particular technological outcome than does discount rate. Sensitivity analysis is also of use in identifying those inputs that have the greatest affect on outputs, allowing the values for those inputs to be refined in further analyses.

Sensitivity analysis approaches can be classified as being either brute-force or implicit. One of the most common types of brute force sensitivity analysis is Nominal Range Sensitivity Analysis (NRSA). Using NRSA, one first identifies the inputs to be considered in the sensitivity analysis. Next, the endpoints of the plausible range for each input are identified. One would then conduct a new MARKAL run for each endpoint of each selected input, with the other inputs held at their baseline values. Thus, if there were 10 inputs considered in the sensitivity analysis, 20 runs would be required. The results could then be plotted or presented in a table to illustrate the response to changes in each parameter.

Implicit sensitivity analysis does not make use of iterative runs as in the brute force approaches, but instead examines the outputs of the MARKAL solutions to infer sensitivity information. For example, typical linear programming (LP) solutions (like those generated by MARKAL) include information that characterizes

- how much the optimal solution will change with an incremental change to the bounds on each constraint, and
- the amount that any constraint can be changed before the optimal solution changes. An advantage of implicit techniques is that they do not require additional runs to provide this information.

These techniques are expected to provide information that will be useful in understanding and evaluating MARKAL results. Thus, a major step will be to design and carry out a sensitivity analysis.

7.5.3 Uncertainty analysis

Modeling activities often involve a high degree of uncertainty. Sources of uncertainty include measurement error, sampling bias, spatial and temporal averaging, and imperfect model formulation. Failure to account for these uncertainties may suggest to analysts and decision-makers that there is a higher degree of precision in model results than is actually the case.

Uncertainty analysis involves the characterization of how uncertainties in the inputs to an assessment affect uncertainties in the outputs of the assessment. Thus, one outcome of an uncertainty analysis is a representation of the uncertainty in each critical assessment output. Depending on the level of characterization of uncertainties in inputs, this representation may range from a qualitative descriptor, to a set of high and low bounds, to a probability density function. The analysis may also result in a ranking of uncertain inputs that characterizes their relative influence on uncertainties in outputs. Such information is useful in allocating resources most efficiently for increasing the precision in assessment outputs.

Uncertainty analysis approaches typically involve propagation of uncertainties through a model. Propagation techniques fall into the categories of analytical, approximation, and numerical. Analytical techniques are useful for problems involving linear summations and simple statistical distributions for inputs. Approximation methods are similar, but allow application to a wider range of problems through Taylor series expansions or similar approaches. These techniques are very limited for problems that are nondifferentiable, however. Numerical propagation algorithms are computationally intensive, but are well suited to address most uncertainty analysis problems, including those that are nonlinear, non-differentiable, or that involve empirical descriptions of uncertainty. Monte Carlo simulation is a commonly used technique in this class. Using regression-based approaches, Monte Carlo results can be analyzed to provide sensitivity information. For example, standardized regression coefficients provide the relative impact of changes in each input on changes in each output.

A short-term task for uncertainty analysis is to evaluate the types of uncertainty information available for various inputs to the assessment. For example, inputs may best be characterized as ranges, with alternate values, or as statistical functions. Based on how uncertainties are characterized, the team will identify the most appropriate propagation and analysis approaches. These approaches will take into account the linear nature of the MARKAL model, and will likely involve Monte Carlo simulation, followed by regression analysis. Alternative approaches will be evaluated for applicability as well. Once a scheme has been selected, the uncertainty analysis will be carried out and the results characterized both tabularly and graphically. The approach and results of the uncertainty analysis will be characterized and reported along with other project documentation.

7.6 Integration of MARKAL Modeling Results into the ORD Air Quality Assessment

A range of technological change scenarios developed by TACT ultimately will be integrated into ORD’s Air Quality Assessment. Thus, it is important that any outputs that are generated include the appropriate information to inform that assessment and be in a format that can readily be integrated. To ensure that this is the case, TACT has begun to work with members of EPA's National Exposure Research Laboratory (NERL) and Office of Air Quality Planning and Standards (OAQPS) to define the various linkages between the models that will be used in the assessment. This ongoing examination of the ORD Air Quality Assessment modeling framework has identified a number of issues that must be considered. Examples include:

- Pre- and post-processing modules will be needed for many of the models, so MARKAL technological outputs can be assimilated.
- To ensure that the economic assumptions used in our MARKAL runs are consistent with those used to develop inventory growth factors, and to consider the effects of energy price changes on sector growth, it may be desirable to run MARKAL and an economic model iteratively, converging to an equilibrium economic condition.
- The current model used to make emissions projections, the Economic Growth Analysis System (EGAS), uses a simple, regression-based approach for correlating the relationship between economic growth and emissions. MARKAL potentially provides a more realistic projection. EGAS should therefore be modified to use projection results from MARKAL.

Discussions with OAQPS and NERL will continue until all such issues have been identified and plans for addressing those issues have been determined.

Appendix A
MARKAL

A MARKAL database uses a variety of data parameters to describe each element of the RES. A small number of system-wide parameters are also used to tell the model how to handle technologies across the RES. The general categories of data required for a MARKAL model are

- System-Wide Parameters,
  - discount rate
  - seasonal/day-night fractions
  - electric reserve margin
- Energy Service Demands,
- Energy Carriers,
- Costs,
  - resource
  - investment
  - fixed
  - variable
  - fuel delivery
  - hurdle rates
- Resource Technologies,
  - resource supply steps
  - cumulative resources limits
  - installed capacity
  - new investment
- Process and Demand Technologies, and
  - fuels in/out,
  - efficiency
  - availability
- Environmental Impacts
  - Unit emissions per resource
  - technology
  - investment.

This appendix provides a brief description of each of the main types of data required by a MARKAL model. A full description of the parameters is available upon request and will be published separately as part of the complete database documentation.

A.1 System-Wide Parameters

System-wide, or global, parameters are assumptions that apply to the entire model. Two important, system-wide aspects of the model are

- **Cost discounting**—Costs are to be provided in MARKAL for the supply of energy resources and the building and operating of technologies. All costs must be entered in the same monetary unit (U.S. 1995 dollars for the U.S. MARKAL model). All input costs along with those reported from the model are then discounted to a common year. The user must specify this common year and the discount rate to be used.
- **Subdivision of the year into load fractions**—MARKAL subdivides the year into three seasons Z (Z = summer, winter, intermediate) and two times of day Y (Y = day, night). The fraction of the year that is to be assigned to each season and day/night is provided by the user. These subdivisions of the year determine the default percentage of the year for the construction of the electricity and low-temperature heat demands. The user must specify the fraction of the year that is to be assigned to each of these six subdivisions.

A.2 Energy Service Demands

Energy service demands describe the requirement for specific end-use energy services to be delivered to individuals and the economy. Examples of energy services include residential lighting, personal automotive transport, and industrial process heat. The demand for an energy service does not refer to consuming a particular energy commodity, but rather to providing *services* such as manufacturing steel, moving people, lighting offices, and heating homes. These energy services are measured in units of useful energy, which may vary with sector. For example, in the U.S. model, demand for the majority of transport services is measured in miles traveled, while the demand for industrial process energy is measured in petajoules (PJ).

MARKAL is a demand driven model. In most formulations of the model, the objective is to satisfy all of the energy service demands at the least possible cost, subject to a variety of system and user-imposed constraints. Each demand is met by the sum of the output from all technologies that serve that demand. For example, the demand for personal travel can be serviced by a variety of cars and light trucks. For the standard MARKAL model, demand for energy services must be specified exogenously by the user. In other model variants, MARKAL-MACRO and MARKAL-Elastic Demand, demand levels are determined endogenously in response to prices.

Key demand related data includes

- projections for useful energy demand services by sector, and
- The load shape of the demand pattern by season/day-night, when the sector includes demand devices that consume electricity or low-temperature heat.

A.3 Energy Carriers

Energy carriers are the various forms of energy produced and consumed in the RES depicted in a MARKAL model. Energy carriers can include fossil fuels, such as coal with different sulfur content, crude oil and oil products, electricity to different grids, synthetic fuels produced by model processes, and renewable energy (e.g., biomass, solar, geothermal, hydro). Energy carriers provide the interconnections between the various technologies in a MARKAL model by flowing out of one or more technologies and into others. The model requires that the total amount of each energy carrier produced is greater than or equal to the total amount consumed.

All energy carriers are tracked annually with the exceptions of electricity (which is divided into three seasons and day/night) and low-temperature heat (which is tracked by seasons).

Key energy carrier related data includes

- Overall transmission efficiency (usually 1 except for electricity and low-temperature heat grids) for all energy carriers, and
- For electricity and low-temperature heat:
    - investment and operation and maintenance cost for transmission and distribution systems,
    - reserve margin, or amount of installed capacity above the highest average annual demand (usually higher than the traditional utility reserve margin because it is the level above the average peak period load, not the peak itself).

A.4 Resource Technologies

Technology characterizations are the heart of a MARKAL model. Resource technologies represent all flows of energy carriers into and out of the system, including imports and exports, mining and extraction, and renewable energy flows. These technologies are generally characterized using stepwise supply curves that indicate how much of a resource can be obtained at each of a set of prices during each model period. For example, in the U.S. model, imported electricity is modeled using a three-step curve, whereas mining various grades of coal is represented using eight-step curves.

Key resource technology data includes

- Bounds indicating the size of each step on each resource supply curve (These bounds might arise for technical reasons, such as a limitation on the amount of oil that can be produced from a particular reservoir in a given year, or for economic reasons.),
- A corresponding resource supply cost for each supply step, and
- Cumulative resources limits indicating the total amount of a resource supply step that can be delivered over the entire modeling horizon (e.g., total proven size of a petroleum reservoir).

A.5 Process and Demand Technologies

Process technologies are those that change the form, characteristics, or location of energy carriers. Examples of process technologies in the U.S. model include oil refineries and hydrogen production technologies. A subcategory of the process technologies is the conversion technologies, which model electricity and low temperature heat production. Demand technologies are those devices that are used to directly satisfy end-use service demands, including vehicles, furnaces, and electrical devices. These technologies are characterized using parameters that describe technology costs, fuel consumption and efficiency, and availability.

Key process and demand technology data include

- Technology costs,
  - cost of investing in new capacity,
  - fixed operating and maintenance (O&M) costs for installed capacity,
  - variable O&M costs according to the operation of installed capacity,
  - fuel delivery costs corresponding to any sectoral difference in the price of an energy carrier,
- Energy carriers into and out of each technology,
- The technical efficiency (usually defined as the ratio between the sum of energy carrier or useful energy service outputs to the sum of energy carrier inputs),
- The model year in which the technology first becomes available for investment,
- Availability factors (for process technologies) and capacity utilization factors (for demand technologies) that describe the maximum percent annual (or season/day-night) availability for operation or a fixed percent annual (or

season/day-night) capacity utilization per unit of installed capacity,

- The current existing installed capacity,
- Limits on capacity in the form of incremental new investment (absolute or growth rate) or total installed capacity (Such bounds may be set for economic, technical, behavioral, or other reasons.), and
- Hurdle rates, or technology specific discount rates, that can be used to represent non-economic, behavioral aspects of investment choices (e.g., consumer preferences, expectation of very rapid rates of return, information gaps). Often the “real world” does not make decisions based strictly upon the least-cost perspective that MARKAL uses. These impediments to the market can be represented to MARKAL as technology-specific discount rates, higher than the systemwide discount rate, for such technologies.

A.6 Environmental Variables

MARKAL has the capacity to track the production or consumption of environmentally relevant quantities according to the activity, installed capacity or new investment in capacity of a resource or technology. This capacity has most often been used to track emissions of traditional pollutants such as CO_2, NO_X, sulfur oxides, VOCs, and particulates. However, it could also be used to track consumption of land or other resources or the removal of pollutants from the system.

Key environmental variable related data (expressed in terms of pollutant emissions) include

- Emissions per unit of technology activity, installed capacity, or new investment,
- Emission constraints, which can take the form of a cap on total emissions in a year or a cumulative cap on emissions over the entire modeling horizon, if desired,
- Taxes, which can be applied to each unit emitted, by sector/technology, if desired.

Appendix B
Database Development, Review, and Calibration

This Appendix describes the EPA MARKAL RES database development, including data sources, peer review, and calibration.

B.1 Data Sources

Wherever possible, data was taken from NEMS input data underlying the AEO 2002 (U.S. EIA, 2001). AEO data was selected for the RES because it is a nationally recognized source of technology data, widely used where reference or default data are required. In some cases, AEO data were not available in a form that could be utilized for the EPA MARKAL model. The table below lists the data sources used for each sector as well as the number of technologies/resources in each sector.

Table 13. Primary Sources Used in Developing the Database.

Sector	Data Source	Data Quality[a]	Number of Technologies/Resources
Transportation	OTT QM DeCicco et al., 2001	A B	15 personal vehicles in 5 size classes; 40 other passenger & freight technologies
Commercial	NEMS	A	300
Residential	NEMS	A	135
Industrial	SAGE (under development)	A	~100
Electricity	NEMS EPRI TAG	A C	45
Resource Supply	NEMS	A	25 coal types, 10 imported petroleum products, domestic and imported oil and natural gas

[a] Data quality definitions can be found in the Quality Assurance Plan (Shay et al., 2003)

The AEO is a nationally recognized source of technology data that is widely used where reference or default data is required. It presents mid-term forecasts of energy prices, supply, and demand. The projections are based on results from EIA's NEMS (U.S. EIA, 2003a) and are based on federal, state, and local laws and regulations in effect at the time of the model run. (EIA, Site 1.)

Because the majority of the RES data used in these analyses are coming from EIA's NEMS database, the quality level of the data drawn from them is of particular interest. EIA has performance standards to ensure the quality (i.e., objectivity, utility, and integrity) of information it disseminates to the public. Quality is ensured and maximized at levels appropriate to the nature and timeliness of the disseminated information. EIA also strives for transparency about information and methods in order to improve understanding and to facilitate reproducibility of the information.

For a complete description of EIA's Quality Guidelines see EIA, Site 2.

For the transportation base case sector, the data are drawn from the U.S. DOE's OTT QM assessment. QM describes the analytical process used in estimating future energy, environmental, and economic benefits of U.S. DOE EE/RE programs. QM seeks to monitor and measure the impacts of all DOE EE/RE programs and to summarize their overall national effects. Quality Metrics has been an active annual DOE EE/RE-wide analysis and review procedure since 1995 (U.S. DOE, 2002).

Data for the electricity sector was drawn from NEMS with supplemental data pulled from the EPRI TAG (EPRI, 1993). EPRI is a non-profit energy research consortium providing scientific research, technology development, and product implementation for the energy industry. The TAG is a standard reference work for the energy industry that characterizes key electric generation technologies and their operation, costs, environmental impacts, etc.

Ongoing efforts to develop the industrial sector representation are centered on adapting the characterization used in EIA's SAGE model (U.S. DOE, 2003c). This characterization describes six energy services within each of six industrial sectors. Additional documentation will be provided when this sector's development work is complete.

Data were then aggregated and transformed into MARKAL units as necessary.

B.2 Peer Review

Each sector's data and documentation was then sent to several experts in that sector for review. Peer review questions included:

- Has an appropriate data source been used for the sector?
- Has that data been used appropriately?

- Do the relative costs and performance of the technologies/resources look reasonable?
- Are there technologies that should have been included that were not, or that have been included that should not?

Table 14 lists the peer reviewers by sector.

Table 14. Sector Peer Reviewers.

Sector	Invited	Accepted	Responded	Individuals
Residential	11	7	3	John Cymbalsky (EIA/DOE) Jonathon Koomey (LBNL[a]) Jim Sullivan/Glenn Chinery (EPA/CPPD[b])
Transportation	9	6	5	Roger Gorham (EPA/OTAQ[c]) Therese Langer (ACEEE) Steve Plotkin (ANL[d]) John DiCicco (EDF[e]) Don Hanson (ANL)/Marc Melaina (U. Mich)
Resource Supply	13	4	4	Floyd Boilanger (DOE/NETL[f]) Casey Delhotal (EPA/CPPD) Russell Jones (API[g]) John Conti/Kaydes (EIA/DOE)
Electricity	16	9	3	Floyd Boilanger (DOE/NETL) Dallas Burtraw (RFF[h]) Russell Noble (Southern Companies)
Commercial	11	5	4	Jim Sullivan (EPA/CPPD) Harvey Sachs (ACEEE) Erin Boedecker (EIA/DOE) Jonathon Koomey (LBNL)

[a] LBNL = Lawrence Berkeley National Laboratory.
[b] CPPD = Climate Protection Partnerships Division.
[c] OTAQ = Office of Transportation and Air Quality.
[d] ANL = Argonne National Laboratory.
[e] EDF = Environmental Defense Fund.
[f] NETL = National Energy Technology Laboratory.
[g] API = American Petroleum Institute.
[h] RFF = Resources for the Future.

In general, peer review responses indicated that the data sources and TACT's use of the data were appropriate. Several minor errors and omissions were identified and corrected. The reviewers also made several suggestions for future technologies that could be examined through scenario analysis in sectors beyond transportation. A document describing the peer review comments and our responses in greater detail will be provided with the database documentation when the database is released.

B.3 Calibration

Following the incorporation of peer review comments and any necessary changes into the RES database, the model was run for comparison and calibration to AEO 2002 results. AEO 2002 was selected as a calibration benchmark for two reasons. First, the Annual Energy Outlook is a nationally recognized short to mid-term energy technology and consumption forecast, widely used where a reference forecast is required. Second, much of our RES data was derived from AEO 2002 input data.

The goals of the calibration are

- to ensure that the model is producing reasonable results, given its input assumptions,
- to determine whether the model is providing a plausible, consistent representation of the key features of the U.S. energy system,
- in cases where our results differ from AEO results, to be able to identify why the differences exist, and
- to identify any significant errors in the construction or characterization of the RES.

Comparing model results to AEO 2002 encompassed total energy consumption for each (AEO Table 1), by sector (AEO Table 2), and within sector by use (AEO Tables 4-9 and Supplemental Tables). First, it was determined whether or not broad trends (upward, downward, or changing over the time horizon) were tracked by MARKAL model results. Then, the degree of quantitative match between MARKAL results and AEO 2002 was determined.

NEMS, the model used to produce AEO 2002, differs in many respects from MARKAL. In general, NEMS sectors are modeled in more detail, more aspects of consumer and producer behavior are simulated, and the model is generally more conservative about switching fuels and technology types than is MARKAL. Therefore, unconstrained MARKAL results are not expected to match AEO results exactly.

In some cases, constraints were added to force MARKAL to track AEO more closely. The decision to use constraints to force MARKAL to track AEO involves trade-offs between desired model characteristics. On the one hand, it is desirable to make sure that MARKAL's behavior is realistic in that it represents real constraints and inflexibilities in the energy system. On the other hand, AEO results are a simulation of NEMS modelers' judgment about the most likely direction of the energy system, whereas we are using MARKAL to explore a variety of scenarios for the system's future evolution. Therefore, it is not desirable to force MARKAL to track AEO so closely that it lacks the flexibility to respond with different outcomes to differing input assumptions.

Constraints were added where there is an underlying feature of the energy system that an unconstrained MARKAL run does not represent. These constraints have been highlighted within the model and made easily adjustable by the user. Documentation of these constraints and the spreadsheets necessary to adjust them will be provided when the model is released.

Examples of these constraints include fuel switching, personal vehicle classes, and availability of electricity generation from renewable sources.

Fuel switching—In the commercial and residential sectors, NEMS contains built-in mechanisms that inhibit fuel switching for end-use applications where more than one fuel is available. In both sectors, NEMS tracks new floorspace separately from existing. In the commercial sector, when selecting the technologies for existing floor space, NEMS requires a significant percentage of these to use the same fuel as did the previous technologies serving that space. In the residential sector, NEMS imposes a cost representing investment in necessary technologies (e.g., ductwork) when fuels are switched in existing homes. The MARKAL database described here does not track new and existing space separately, so constraints have been added limiting the rate of fuel switching in the sectors over time. For commercial and residential space and water heating, 1995 fuel splits are constrained to historical values. These constraints are then relaxed by 3 percent each model period. This relaxation rate is adjustable by the user.

Personal vehicles size classes—An unconstrained MARKAL run would satisfy all demand for personal vehicle travel using the least cost options, which in most cases would be compact cars. In order to prevent this unrealistic behavior, the model has been constrained to maintain the 1995 model year market shares in its purchases throughout the model time horizon. This split is adjustable by the model user. Unlike fuel switching, this constraint is not allowed to relax over time because the model would simply switch back to compact cars.

Renewable electricity generation technology availability—Cost and performance characterizations of renewable electricity generation technologies were derived from AEO 2002 input assumptions. These costs assumptions are adjusted within NEMS according to yearly and cumulative capacity installations, representing the effects of technology learning (decreasing costs) and of site quality, necessary transmission network upgrades, and market pressures from competing land uses (all increasing costs). In practice, this means that the costs assumptions that have been put into MARKAL are appropriate only for a limited increasing capacity. To represent this limitation, total installed capacity of these technologies is constrained to follow AEO projections. (In practice, these constraints are not binding in the scenario results we report on here.) These characterizations and constraints will be replaced by a thorough scenario analysis considering technology cost and performance and resource availability when the electricity generation scenario analysis is performed.

In representing the broad trends of energy consumption out to 2020, MARKAL runs described here track AEO. The largest deviation occurs in the electricity generation sector, where MARKAL runs are consistently consuming more coal and less natural gas than AEO projects. It is anticipated that this deviation will disappear when emissions and emission control technologies in this sector are extensively reviewed and updated during the first six months of 2004.

Total energy consumption in the commercial sector is within 10 percent of AEO values. For the two major fuels in the commercial sector, electricity consumption is within 10 percent and natural gas is within 20 percent. Within specific end uses, MARKAL consumption differs by more than 20 percent from some AEO values. This difference primarily arises because NEMS differentiates between 11 different commercial building types, whereas MARKAL treats the commercial sector as a single unit. Because some equipment types are applicable to only certain building types, NEMS achieves a more detailed picture of the use of equipment types by building types. Because the commercial sector is not the focus area here, that tracking AEO commercial sector energy use at the broad level was deemed sufficient for the purposes of this report. Commercial sector calibration will be revisited in future analyses.

In the residential sector, total fuel consumption is within 5 percent of AEO values, electricity consumption is within 10 percent, and natural gas consumption is within 10 percent until 2020, at which point it is within 20 percent. The major deviation of MARKAL results from AEO results in this sector is that MARKAL chooses to exercise its fuel switching option, making its most significant investments in new water heating capacity in LPG-fueled devices, more than doubling LPG consumption for this end-use over the AEO time horizon. By contrast, AEO results do not project any increase in LPG-fueled water heating. This difference arises because NEMS imposes a significant distribution cost on LPG to the residential sector which this MARKAL database does not presently replicate. Because the residential sector is not the focus area here, this degree of conformity between MARKAL and AEO results was deemed appropriate. Fuel distribution costs will be revisited in future analyses.

In the transportation sector, energy consumption by subsector for non-light-duty applications is within 10 percent of AEO values for trucks, buses, air, passenger rail, and water freight. For rail freight, the difference between our results in AEO values grows to 20 percent by 2020. This difference arises because of the way efficiencies for diesel rail freight technologies, which were retained from the 1997 DOE MARKAL database, were mapped into MARKAL. Technology characterizations for non-light-duty transport applications will be reviewed and updated as necessary in future analyses. Consumption of the two major fuels in the non-light-duty subsectors, jet fuel and diesel fuel, is within 10 percent of AEO values.

NEMS represents light-duty vehicles very differently from these OTT-derived MARKAL representations. NEMS represents a number of vehicle component technologies (including engines, transmission, and tire types) and a variety of efficiency improvements and optimizes vehicle packages built from these technologies during its runs. Therefore, not all of the scenario results are expected to track AEO results exactly with respect to technology choice and fuel consumption. In addition, these scenarios have focused on gasoline-fueled vehicles and hydrogen FCVs and have excluded from consideration the variety of alternative fuels that AEO considers, including alcohol-based and natural gas-based fuels. (These alternative fuels will be examined during the next phase of the transportation scenario analysis.) Finally, these analyses have considered a wider range of scenarios than AEO, involving considerable variation in fuel prices and technology price, performance and availability.

The Conventionals Dominate scenario resembles AEO most closely in its mix of vehicles (AEO projects 94 percent conventional cars and 89 percent conventional light trucks in 2020), and its light-duty gasoline consumption closely tracks AEO projections (see Table 15). Other scenarios that feature greater penetration by more efficient vehicles will show lower gasoline consumption than AEO projections. The Hybrid Market HM(C) scenario results are shown for comparison. They deviate significantly from AEO values as more efficient vehicles penetrate the market from 2010 on.

The electricity generation sector is the most complex to calibrate because of availability constraints and base load and peaking requirements. In the electricity generation sector, total generation is within 5 percent of AEO values in each model year. As noted above, these MARKAL runs are consistently consuming up to 25 percent more coal (and less natural gas)

Table 15. Comparison of MARKAL results to AEO 2002.

Scenario	Light-Duty Gasoline Consumption (PJ)				
	2000	2005	2010	2015	2020
AEO 2002	15,548	17,098	18,743	20,251	21,477
Conventionals Dominate	15,573	17,463	19,082	20,435	21,763
Hybrid Market [HM(C)]	15,564	17,104	15,916	13,591	11,514

than AEO projections. Emissions control device characterizations and requirements are still in development, and it is believed that this discrepancy will disappear when that work is complete. In addition, MARKAL's petroleum-fired generation does not fall off as quickly as AEO projects and renewable generation does not increase as quickly as AEO projects. Considerable effort will be devoted to the characterization of technologies in the electricity generation sector as TACT moves into scenario analysis in this sector, and TACT expects to resolve these calibration issues in the process.

Because the electricity generation sector is not a major consumer of petroleum (the primary transportation fuel), calibration issues in the electricity generation sector are not expected to affect transportation results, with the exception of the early hydrogen economy scenarios. Because hydrogen production processes consume electricity and/or natural gas (a major fuel in the electricity generation sector) changes in electricity sector results, particularly as they affect the prices of electricity and natural gas, will affect hydrogen scenario results. These issues will be further examined as TACT works with hydrogen and electricity generation scenarios.

Appendix C
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