ABSTRACT

DEGOLYER, JESSICA SUZANNE. Fuel Life-Cycle Analysis of Hydrogen vs. Conventional Transportation Fuels. (Under the direction of Professors E. Downey Brill, Jr. and S. Ranji Ranjithan.).

Fuel life-cycle analyses were performed to compare the affects of hydrogen on annual U.S. light-duty transportation emissions in future year 2030. Five scenarios were developed assuming a significant percentage of hydrogen fuel cell vehicles to compare different feedstock fuels and technologies to produce hydrogen. The five hydrogen scenarios are: Central Natural Gas, Central Coal Gasification, Central Thermochemical Nuclear, Distributed Natural Gas, and Distributed Electrolysis. The Basecase used to compare emissions was the Annual Energy Outlook 2006 Report that estimated vehicle and electricity mix in year 2030. A sixth scenario, High Hybrid, was included to compare vehicle technologies that currently exist to hydrogen fuel cell vehicles that commercially do not exist. All hydrogen scenarios assumed 30% of the U.S. light-duty fleet to be hydrogen fuel cell vehicles in year 2030. Energy, greenhouse emissions, and criteria pollutant emissions including volatile organic compounds, particulate matter, sulfur dioxides, nitrogen dioxides, and carbon monoxide were evaluated. Results show that the production of hydrogen using thermochemical nuclear technology is the most beneficial in terms of energy usage, greenhouse gas emissions, and criteria pollutant emissions. Energy usage decreased by 36%, greenhouse gas emissions decreased by 46% or 9.6 x 10^8 tons, and criteria emissions were reduced by 28-47%. The centrally-produced hydrogen scenarios proved to be more energy efficient and overall release fewer emissions than the distributed hydrogen production

scenarios. The only hydrogen scenario to show an increase in urban pollution is the Distributed Natural Gas scenario with a 60% increase in SOx emissions.

Fuel Life-Cycle Analysis of Hydrogen vs. Conventional Transportation Fuels

by
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DEDICATION

To my Mother and Father for their support throughout my life

BIOGRAPHY

Jessica DeGolyer received her Bachelor of Science degree in Civil Engineering with a minor in Environmental Engineering from the University of Tennessee, Knoxville, in 2004. During the period at University of Tennessee she interned at Hartford Steam Boiler Reliability Technologies in Houston, Texas working in maintenance and reliability engineering, Clarkson University in Potsdam, New York performing research on wind turbines, General Electric in Wilmington, North Carolina working in wastewater and quality control. She then attended North Carolina State University in Raleigh, North Carolina where she worked as a research and teaching assistant in the environmental engineering program during the period of 2004-2006. During the same period, she worked at the U.S. Environmental Protection Agency in Research Triangle Park on hydrogen fuel life-cycles. Jessica DeGolyer currently works as a consultant in land development for Withers & Ravenel, Inc. in Wilmington, North Carolina.

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Chapter 1

Hydrogen: A Potential Alternative to Conventional Transportation Fuels

1.1 Gasoline/Diesel and the Personal Automobile

In the United States, travel by automobile is the primary mode of personal transportation. Automobiles powered by an internal combustion engine and fueled by gasoline have been around since the late 1800s. Today, the amount of vehicle miles traveled continues to climb as the population increases and urban sprawl takes place. Vehicle miles traveled increased 2.5% from 2003 to 2004 [6]. Americans traveled nearly 3 trillion miles in 2004 consuming 103 billion gallons of gasoline [2, 6]. This enormous demand for liquid fossil fuels has created unhealthy levels air pollution.

1.2 U.S. Transportation Emissions

An estimated 158 million people in the U.S. live in areas with unhealthy concentrations of air pollution [4]. The majority of areas exceeding recommended health-based standards, or non-attainment areas designated by the U.S. EPA, are cities. A significant contributor to urban air pollution is transportation emissions. Criteria pollutants such as nitrogen oxides, carbon monoxide, and ozone can all be attributed to the combustion of gasoline and diesel fuels. Alternative transportation fuels will be needed in the future as petroleum supplies diminish and air quality worsens. The combustion of gasoline and diesel emits several air pollutants such as nitrogen oxides, carbon monoxide, particulate matter, and sulfur oxides, all pollutants regulated by the U.S. Environmental Protection Agency (EPA) due to their negative effect on human health. In fact, several U.S. counties exceed the recommended health-based standards. More than half of the all Americans live in the 462 counties (March 2006) that consistently have high concentrations of ground-level ozone and violate EPA standards [4]. Most of these counties exceeding EPA standards are metropolitan areas affected by transportation emissions leading to smog, ground-level ozone, high particulate matter, and air toxics.

Air toxics such as benzene are part of the composition of gasoline and are released through evaporation or incomplete combustion. Other air toxics are by-products of incomplete combustion such as formaldehyde, acetaldehyde, diesel particulate matter, and 1,3-butadiene [1]. Half of all cancers caused by outdoor sources are estimated to be caused by air toxics released from mobile sources [3].

Other pollutants not characterized as detrimental to human health but cause global warming are greenhouse gases (GHG). The transportation sector is the most rapidly growing source of greenhouse gas emissions in the U.S. accounting for 27% of all GHG emissions in 2003 [7].

How do we solve the problem of transportation and the air pollution that is subsequently released? A reduction in air pollution created by automobile transportation could be achieved in several different ways including: changing lifestyle or means of transportation, improving efficiency of conventional vehicles, switching to alternative fuels, or introducing new vehicle technology.

1.3 Interest in Hydrogen Fuel

Alternative fuels to gasoline and diesel will be needed as air quality and the impacts of global warming worsen. The current list of alternative fuels includes ethanol, methanol, liquefied petroleum gas, compressed natural gas, biodiesel, and hydrogen. All of the alternative fuels are generally available to the public in limited areas of the country with the exception of hydrogen. Hydrogen is currently being researched and developed as a possible alternative to gasoline and diesel for use in vehicles. The introduction of hydrogen fuel cell vehicles would cause a fuel switch as well as introduction of new vehicle technology.

1.4 Hydrogen's Elemental Properties

Hydrogen is the lightest and most abundant element on earth. Pure hydrogen does not naturally exist in large quantities but is bound in other substances such as water or hydrocarbons. If pure hydrogen is to be used as a transportation fuel it must be extracted from a hydrogen-rich feedstock such as water, coal, or natural gas. Pure hydrogen can be combusted in a conventional internal combustion engine, but this approach will not be analyzed in this study due to the nitrogen oxides released from combustion of hydrogen.

1.5 Hydrogen Fuel Cell Vehicle

Hydrogen fuel cell vehicles (H_2FCV) use pure gaseous or liquid hydrogen to run an electric motor. Fuel cell plates (in the presence of a catalyst) strip electrons from the H_2 molecules producing electricity and leaving H^+ ions. The hydrogen ions pass through the fuel cell and combine with oxygen from the air to form water; therefore, H_2FCVs emit zero tailpipe emissions. Eliminating tailpipe emissions from vehicles has an enormous potential to improve urban air quality. Moreover, fuel cell vehicles are expected to be 2-3 times more energy efficient than the internal combustion engine vehicles. Removing tailpipe emissions and gaining efficiency will improve end-use transportation emissions. Since hydrogen needs to be extracted from another feedstock source using energy, however, a fuel life-cycle analysis needs to be produced to determine whether hydrogen fuel cell vehicles will cause a net increase or decrease in overall emissions.

1.6 Objective

The objectives of this research are to develop potential future scenarios for hydrogen fuel cell vehicle penetration and to generate and analyze fuel life-cycle emissions associated with each hydrogen extraction pathway. A future with hydrogen fuel cell vehicles and the associated fuel life-cycle emissions will then be compared to a "business-as-usual" future with gasoline/diesel and the associated fuel life-cycle emissions to determine net changes in emissions. Specifically, net changes in criteria pollutants (nitrogen oxides, carbon monoxide, sulfur oxides, particulate matter, and ozone) and greenhouse gases (carbon dioxide, nitrous oxide, and methane) are evaluated.

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Chapter 2

Fuel Life Cycle Studies Involving Hydrogen Fuel

2.1 Hydrogen Fuel Life-Cycle Studies

Recent interest in hydrogen fuel and emissions associated with the fuel life-cycle is reflected in a number of studies that have been released in recent years and are listed and reviewed below. The majority of relevant fuel life-cycle studies have been conducted by the creator of the GREET model, Michael Wang, in association with Argonne's National Laboratory's Center for Transportation Research. Several of the studies directly contributed to the improvement of the GREET model. Studies evaluated in the following literature review are limited to fuel life cycle of U.S. vehicles or the U.S. vehicle fleet. Many studies have been performed in Europe, but focus on locations in Europe, and therefore were not included in this review. The overall trend shown by the studies reviewed is that hydrogen fuel pathways reduce emissions when compared to conventional petroleum-based fuels. Each study evaluated different hydrogen fuel cell vehicle scenarios as well as creating different sets of assumptions for individual scenarios. The following review discusses related works on the subject of estimating and comparing hydrogen fuel life cycle emissions to conventional gasoline/diesel fuel life cycles:

1. "Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems: North American Analysis" was conducted by the General Motors Corporation and Argonne National Laboratory in 2001. The energy companies BP, ExxonMobil, and Shell also participated in this study by providing input and reviewing the

analysis. GM’s study was performed to provide information to public and private decision makers on the energy use and emissions impacts created by various fuels/vehicle technologies in the near-term future. Specifically, this study reported the energy use and greenhouse gas emissions for 27 fuel pathways. Hydrogen, both gaseous and liquid, was considered among various other fuels. Results were compared by incremental units of emission factors; energy use as Btu/mile and emissions as g/mile. The baseline vehicle chosen for this study was the Chevrolet Silverado full-size pickup. The fuel life-cycle was analyzed from well-to-wheel using two different models. The GREET model was used to generate well-to-tank results. GM’s proprietary “Hybrid Powertrain Simulation Program” (HPSP) model was used to generate tank-to-wheel emissions. The GM study discussed results from well-to-tank and tank-to-wheel analyzes as well as the combined well-to-wheel analysis.

When comparing well-to-tank energy demand, results show petroleum-based fuels require the least amount of energy. Natural gas-based fuels show the most energy use, especially liquefied hydrogen. Hydrogen liquefaction requires large amounts of energy making pathways of liquid hydrogen inefficient. Hydrogen produced from an electrolysis process also requires large energy use because of inefficiencies in the electrolysis process and electricity generation. Both imported and North American natural gas-based fuels consumed the most amount of energy compared to the other fuels with the exception of compressed natural gas. When comparing well-to-tank greenhouse gas emissions, petroleum-based fuels show low amounts of GHG. All hydrogen pathways show large amounts of GHG since carbon is released directly from the production of hydrogen or indirectly through electricity generation. Coal and oil-fired electricity production is a large contributor of the carbon emissions released from the overall electricity mix.

The tank-to-wheel results show fuel cell vehicle technology to be more efficient than conventional vehicles due to higher efficiency of the fuel stack especially for the hydrogen fuel cell vehicle. A fuel cell hybrid electric vehicle was also analyzed and found to be 10% more efficient that the fuel cell vehicle technology alone.

The combined well-to-wheel results show the H_2FC HEV to offer the most reduction of greenhouse gas emissions; however, all hydrogen fuel cell pathways reduced greenhouse gas emissions when compared to the conventional gasoline/vehicle pathway.

2. “A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas” was published in December 1999 by M.Q. Wang and H.-S. Huang of Argonne National Laboratory’s Center for Transportation Research. Wang’s study analyzed fuel life-cycles of eight fuels, including hydrogen produced from natural gas. The study presented natural gas as an alternative to oil showing that worldwide natural gas reserves are comparable to oil reserves. Natural gas production however, lags behind oil production. Natural gas reserves are shown to be more stable because only 43% of the world’s natural gas reserves are owned by OPEC as opposed to 77% of oil reserves. This study was performed to not only address alternatives needed to reduce dependence on foreign oil but also to reduce greenhouse gas and criteria pollutant emissions in the transportation sector. The transportation sector at the time of this study consumed 30% of energy use and was predicted to be the fastest growing sector of the U.S. economy. The

transportation sector is the second largest contributor to greenhouse gas emissions just after the industrial sector.

Wang's study used the GREET model. Results were generated and compared in terms of emission factors and compared to the conventional gasoline and diesel fuel pathways. Four scenarios were evaluated for hydrogen fuel from natural gas. Two scenarios assume gaseous hydrogen use, and the other two scenarios assume liquid hydrogen use. The four scenarios were then separated into hydrogen production at central and distributed locations. All hydrogen fuel pathways reduce emissions and energy use when compared to conventional gasoline and diesel. Greenhouse gas emissions show a 55-90% reduction. Reductions in all criteria pollutants also occurred, ranging from 15-100%. Overall the hydrogen scenarios demand 40-60% less energy compared to gasoline/diesel.

3. "Cleaning the Air and Improving Health with Hydrogen Fuel-Cell Vehicles" was released in June 2005 by M.Z. Jacobson, W.G. Colella, and D.M. Golden. Jacobson's study evaluated health and climate benefits/costs of a full fleet replacement of fossil-fuel on-road vehicles with H_2FCVs. This study differs from other fuel life-cycle studies in that it not only analyzed emissions changes, but also how those emissions changes would translate into changes in air pollution. The model GATOR-GCMOM was used to determine air pollution effects with features such as transport, radiation, and atmospheric circulation. The baseline used for comparisons was based on August 1999 emissions. Four scenarios were created to compare to the baseline where a full fleet replacement was assumed. Three hydrogen scenarios were evaluated as follows: hydrogen produced from natural gas, hydrogen produced from wind electrolysis, and hydrogen produced from coal gasification. A fourth

scenario assumed all hybrid electric vehicles to replace conventional fossil-fueled vehicles. The fuel life cycle for each of the scenarios did not include the initial upstream stages which would include mining, storage, processing, and transport of fuels.

Several air pollutants that affect human health were evaluated, including: peroxyacetyl nitrate, carbon monoxide, nitrogen dioxide, toluene, ground-level ozone, and black carbon. Results obtained showed that overall all three hydrogen scenarios greatly improved air pollution due to the removal of tailpipe emissions. Some increases in air pollution occurred regionally in the U.S. due to complex atmospheric reactions that occur. For example, increases in ground-level ozone in Los Angeles and the Northeast corridor were generated due to reducing NOx emissions, which in turn decreased ozone titration and increased OH. H_2FCV scenarios overall decreased greenhouse gas emissions. The scenario with H_2 produced from natural gas increased methane by 40% but decreased carbon dioxide emissions. Water vapor emissions from H_2FCV were shown to be equivalent to water vapor currently released by the complete combustion of gasoline. Overall, hydrogen produced from wind electrolysis has the greatest benefit in terms of health and climate change. Hydrogen produced from natural gas had the second greatest benefit when compared to the baseline. And hydrogen produced from coal gasification and hybrid vehicles had about equivalent benefits. The increased benefit from the HEV scenario of both H_2FCV from wind electrolysis and natural gas is 3700-6400 lives/year and a reduction of 1-3 million cases/year of asthma. H_2FCV wind electrolysis reduces costs by $32-180 billion compared to HEV. Jacobson’s study went on to calculate the cost of producing hydrogen from wind electrolysis since this scenario had the greatest health and climate benefit. The cost of H_2FCV wind electrolysis calculated in the near term is \$3.00-7.40/kg of H_2 or \$1.12-3.20/gallon of gasoline. When the health and mortality cost are added to the market price, the real cost of gasoline increased to \$2.35-3.99/gallon.

4. "Fuel Choices for Fuel-Cell Vehicles: Well-to-Wheels Energy and Emission Impacts" written by the GREET model's creator, Michael Wang, was released in 2002. Wang evaluated fuels for use in fuel cell vehicles including hydrogen and fuels needed for the transition period prior to establishing a hydrogen infrastructure Greenhouse gas emissions and petroleum use were evaluated for the following ten hydrogen production scenarios: centrally produced H_2 from natural gas (both gaseous hydrogen (GH_2) and liquid hydrogen (LH_2)), distributed H_2 production from NG (GH_2 and LH_2), centrally produced H_2 from solar photovoltaic (GH_2 and LH_2), H_2 production via electrolysis using the U.S. grid (GH_2 and LH_2), and H_2 production via electrolysis using renewable energy (GH_2 and LH_2). Wang's results show 8 out the 10 hydrogen scenarios reduce greenhouse gas emissions. The H_2 production via electrolysis using the U.S. grid scenarios increased greenhouse gas emissions due to increased emissions from the electric sector. The centrally produced LH_2 from solar photovoltaic and the H_2 production via electrolysis using renewable energy (GH_2 and LH_2) reduced all greenhouse gas emissions compared to the conventional pathway for gasoline fuel. Petroleum use was nearly reduced by 100% for all hydrogen scenarios.

5. "Contribution of Feedstock and Fuel Transportation of Total Fuel-cycle Energy Use and Emissions" was released by Argonne National Laboratory's Dongquan He and Michael Wang in 2000. Dongquan He's study examined the contribution that the transportation, storage, and distribution of feedstocks and fuels have on the overall fuel life-

cycle. Energy use and emissions were determined for various fuels such as gasoline, diesel, liquid hydrogen, gaseous hydrogen, and other fuels of interest. Prior to He's study, the transportation, storage, and distribution portions of the fuel life cycle were thought to have little impact on overall fuel life-cycle emissions. The five transportation modes evaluated were ocean tanker, barge, truck, rail and pipeline. Energy intensities and distances were determined for each transportation mode to calculate emissions and energy use. Leaks from storing gaseous and liquid fuels also contribute to fuel life cycle emissions. The results show that for some fuels, the transportation, storage, and distribution has a large impact on overall emissions. For petroleum based fuels, approximately 50-60% of the upstream emissions can be attributed to transport, storage, and distribution.

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Chapter 3

A Two Model Approach to Estimate Future Fuel Life-Cycle Emissions

3.1 Fuel Life-Cycles

The fuel life-cycle is the core concept of this study. If hydrogen is to be used as a transportation fuel, it must be produced, and the production of hydrogen requires both resources and energy. This is the reason why comparing the fuel life-cycle and not just the vehicle emissions is vitally important when discussing hydrogen. To demonstrate how fuel life-cycles work, the conventional fuel life-cycle pathway of gasoline is evaluated. First, crude oil must be extracted from the ground. Second, the crude oil must be transported from the location of extraction to a refining facility. In the U.S. the majority of oil comes from outside the country in the form of crude oil and is refined upon arrival to the U.S. The crude oil is then refined and processed into gasoline. Gasoline is then distributed to refueling stations all over the U.S. via pipeline or tanker trucks. And finally, gasoline is consumed in the light-duty transportation sector by internal combustion engines. Every step along the pathway has some associated emissions that make up fuel life-cycle emissions beginning with extraction of the crude oil and ending with combustion of gasoline.

A hydrogen fuel life-cycle looks quite different from the fuel life cycle of gasoline. Hydrogen fuel must be extracted from a source containing hydrogen since pure hydrogen does not exist naturally in abundance. One example of a hydrogen source is natural gas. In Figure 3.1.2., the fuel life-cycle of hydrogen fuel begins with the extraction of natural gas from drilling underground. The raw natural gas is transported to a processing plant via a network of gathering pipelines. The processed natural gas is then transported via pipeline to a steam methane reforming (SMR) plant to extract the hydrogen from the natural gas. The gaseous hydrogen fuel is then delivered throughout the U.S. via pipeline to refueling stations where the gaseous hydrogen is compressed. The hydrogen fuel life-cycle ends with hydrogen fuel conversion in hydrogen fuel cell vehicles. As discussed earlier hydrogen fuel cell vehicles produce no tail-pipe emissions; however, from the extraction of natural gas to the compression of hydrogen fuel at the refueling stations, emissions are created that must be compared to the life-cycle of gasoline fuel.

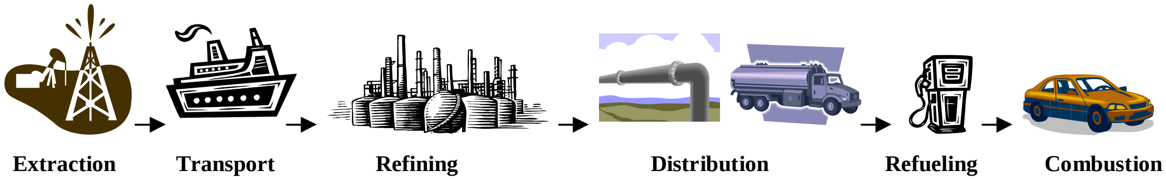


Figure 3.1.1 Fuel Life-Cycle of Gasoline Fuel

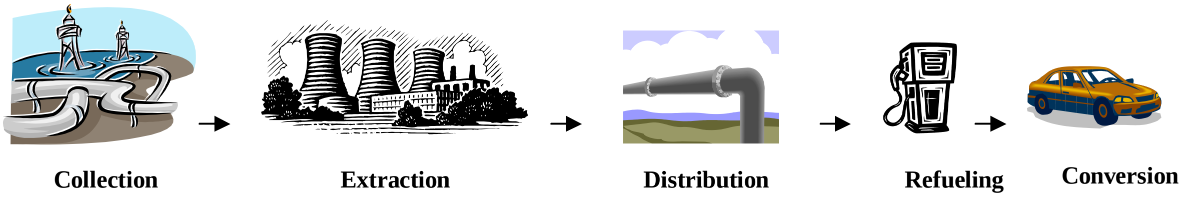


Figure 3.1.2 Example Fuel Life-Cycle of Hydrogen Fuel from Natural Gas

3.2 Hydrogen Scenarios

Emissions comparisons were performed using model year 2030 to represent overall emissions changes due to a 30% replacement in the light-duty vehicle fleet to hydrogen fuel cell vehicles. As discussed earlier in Chapter 1, hydrogen can be extracted from various hydrogen fuel sources. Five hydrogen fuel pathways demonstrating various technologies were used in this study. These pathways, which include natural gas, coal, and water as hydrogen feedstock sources are described below. Each pathway has a different hydrogen production method. All scenarios assume the storage of compressed gaseous hydrogen as opposed to liquid hydrogen at the refueling stations because almost all of the research refueling stations today store gaseous as opposed to liquid hydrogen.

3.2.1 Central Natural Gas Scenario

Producing hydrogen at large central locations using natural gas as the hydrogen fuel source is the example hydrogen pathway discussed above. Natural gas is primarily composed of methane (CH_4). The process of steam methane reforming of natural gas extracts hydrogen by exposing methane to high-temperature steam ranging from 700 to 1000 degrees Celsius in the presence of a catalyst:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

The fuel life cycle of hydrogen fuel produced from the Central Natural Gas Scenario accounts for emissions generated from natural gas extraction, transportation, processing, steam methane reforming, electricity consumption, distribution, and hydrogen compression at refueling stations.

Currently in the U.S., 95% of hydrogen is produced using this process of steam methane reforming of natural gas at large central plants [14]. Today's hydrogen is produced primarily for refining petroleum products and producing chemical fertilizers. This scenario has its advantages in the infrastructure of natural gas pipeline networks that currently exists [14].

3.2.2 Central Coal Gasification Scenario

Gasification is a process where a carbon-based feedstock such as coal is broken down into its elements by a series of complicated chemical reactions. Coal in a gasifier is exposed to steam and low levels of oxygen at high temperatures to produce a synthesis gas composed primarily of hydrogen, carbon monoxide, and carbon dioxide. A second reaction follows where carbon monoxide and water produce carbon dioxide and additional hydrogen. Coal gasification would only be used at large central plants to produce hydrogen as assumed in this scenario. The fuel life-cycle of hydrogen produced by coal gasification takes into account coal mining, transportation, coal gasification, electricity consumption, distribution, and compression at refueling stations. Coal gasification to produce hydrogen fuel is currently in the stages of research and development.

3.2.3 Central Thermochemical Nuclear Scenario

A thermochemical cycle to produce hydrogen fuel involves a chemical process that requires a large amount of heat created by nuclear energy. The thermochemical process assumed in this study uses water as the hydrogen fuel source. A chemical reaction occurs when sulfuric acid is exposed to high temperatures ranging from 800 to 1000 degrees Celsius (needed for high efficiency) and low pressures:

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2\ O_2 \quad (3)$$

Two additional chemical reactions that occur at different temperatures extract pure gaseous hydrogen:

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (4)$$

$$2HI \rightarrow H_2 + I_2 \quad (5)$$

The reactions yield hydrogen and oxygen from water and heat and recycle all other chemical reagents including sulfur compounds. Nuclear energy is needed to provide the heat component for this scenario. Specifically, advanced nuclear energy produced from high-temperature gas-cooled reactor (HTGR) was assumed in this case. Using nuclear energy to produce hydrogen would only be performed on a large scale, and therefore is assumed to be produced at large central plants. The gaseous hydrogen fuel is assumed to be transported to refueling stations throughout the U.S. via a network of hydrogen pipelines. The hydrogen is compressed at refueling stations by natural gas or electric compressors.

Nuclear power plants harness the power of fission to produce energy, not combustion, and therefore do not produce emissions. However, emissions are created during uranium mining, transportation, fuel enrichment, electricity consumption and fuel processing, all of which contribute to the fuel life-cycle emissions released from this scenario. Thermochemical nuclear production of hydrogen is currently in the stages of research and development.

3.2.4 Distributed Natural Gas Scenario

The second scenario that uses natural gas as the hydrogen fuel source to extract hydrogen is Distributed Natural Gas. This scenario is the same as the Central Natural Gas Scenario except the hydrogen is extracted on-site at refueling stations instead of at large central locations. The same method of extraction, steam methane reforming, is used to extract hydrogen except only on a smaller scale. This scenario is considered one of the least cost scenarios due to the natural gas pipelines that already exist in some regions of the country to distribute natural gas to refueling stations. On-site production would also avoid the large start-up costs associated with building the large central plants. Hydrogen produced from natural gas on-site currently exists at several of the hydrogen research refueling stations.

3.2.5 Distributed Electrolysis Scenario

Electrolysis is the second technology that uses water as the hydrogen fuel source (Central Thermochemical Nuclear is the first). Electrolysis is the splitting of water into elemental oxygen and hydrogen. A negatively charged cathode and positively charged anode are placed in water with an electrolyte such as salt while a current is passed between the two plates. The following reactions occur to extract pure elemental hydrogen,

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad \text{[Cathode]} \quad (6)$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad \text{[Anode]} \quad (7)$$

Electrolysis is also the second scenario that can be produced on-site at refueling stations as assumed in this scenario. The Distributed Electrolysis Scenario has an advantage over the Distributed Natural Gas Scenario of not requiring additional infrastructure if sufficient water and electricity are available at refueling stations for hydrogen production. The Distributed Natural Gas Scenario would have the advantage of using existing natural gas pipelines but these pipelines do not exist everywhere in the U.S., and therefore would have to be constructed if hydrogen fuel is to be available everywhere. Hydrogen produced from electrolysis on-site currently exists at several of the hydrogen research refueling stations.

3.3 Basecase Scenario

The Basecase Scenario used to compare with the hydrogen scenarios was created using data from the Annual Energy Outlook 2006 (AEO 2006). AEO 2006 is provided by the Energy Information Administration that represents the "Official Energy Statistics from the U.S. Government." AEO 2006 provides data on future U.S. vehicle fleet mix estimates as well as future U.S. electricity mix estimates. The future vehicle fleet mix estimates assume negligible hydrogen fuel cell vehicle estimates out to model year 2030, and therefore provided a suitable business-as-usual baseline for comparisons.

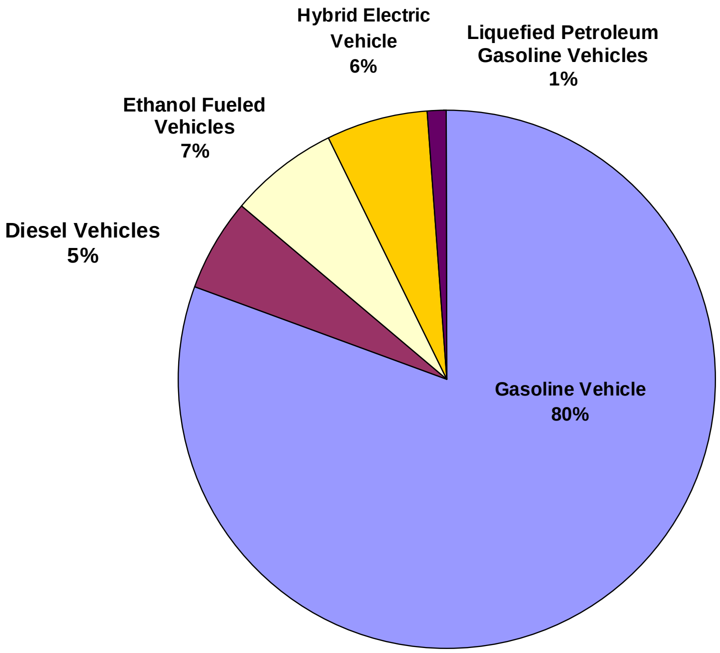


Figure 3.3.1 Basecase Light-Duty Vehicle Mix Estimates in Model Year 2030 (Source: AEO 2006)

3.4 High Hybrid Scenario

A High Hybrid Scenario was included in this study of future emissions since hybrid-electric vehicles have recently emerged in the light-duty transportation sector market. The life-cycle of gasoline used in hybrids needs to be compared to the life cycle hydrogen used in fuel cell vehicles. Figure 3.4.1 shows the vehicle mix assumed in the High Hybrid Scenario.

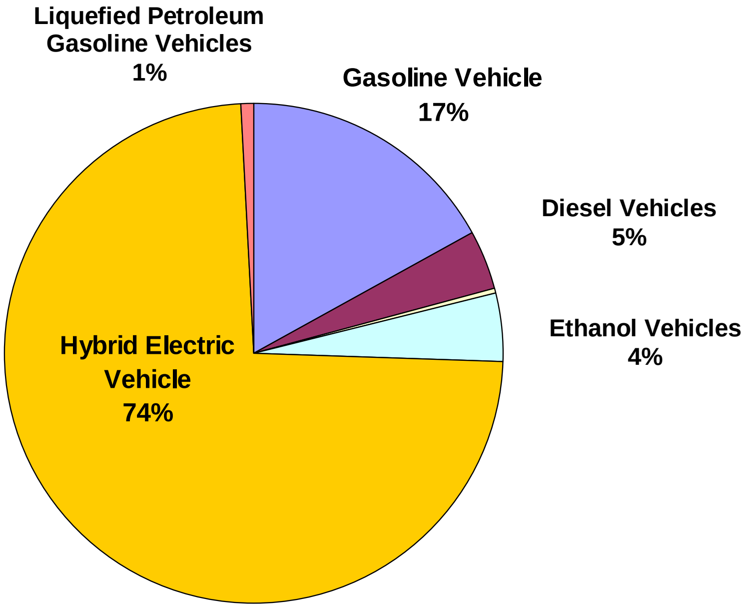


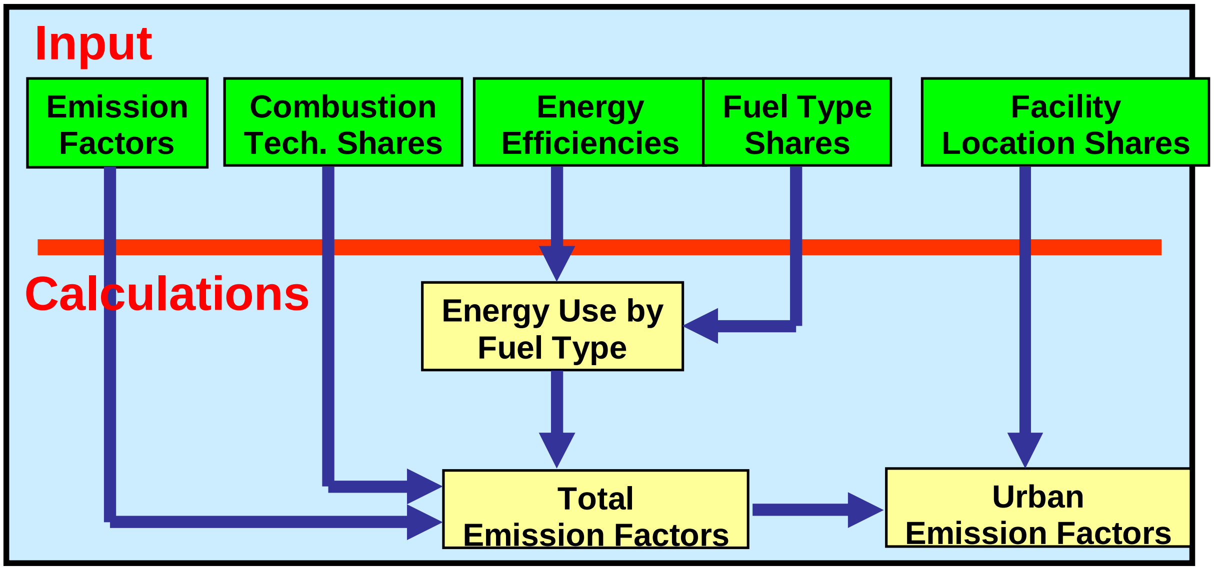
Figure 3.4.1 High Hybrid Scenario Vehicle Mix in Model Year 2030

3.5 MARKAL Model

Hydrogen fuel and fuel cell vehicles were optimistically assumed to represent 30% of the light-duty transportation sector to demonstrate emission changes due to a significant fleet replacement in model year 2030. A large emergence of hydrogen fuel cell vehicles and hydrogen fuel would have a significant impact on the economy. Hydrogen fuel cell vehicles would essentially replace other vehicle types and hydrogen fuel production would affect other sectors of the economy, particularly the electric sector. To determine the effects of hydrogen fuel emergence on the economy, U.S. EPA's Market Allocation Model (MARKAL) was used. MARKAL is a linear-optimization model that incorporates costs to provide realistic economic responses. MARKAL provides output on what vehicles would make up the rest of the vehicle fleet if hydrogen fuel cell vehicles represented 30% of the market. MARKAL also provided responses in the electric sector due to mass production of hydrogen fuel for each of five hydrogen production scenarios. MARKAL was also used to generate vehicle mix and electric mix for the High Hybrid Scenario.

3.6 GREET Model

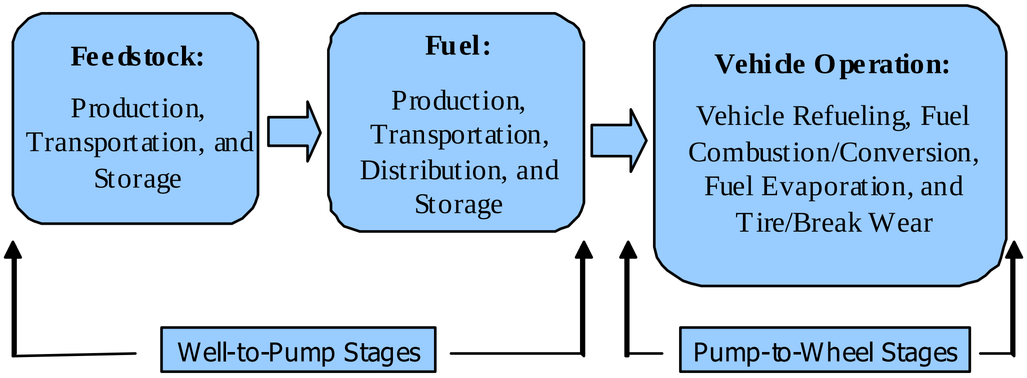
Emissions from the fuel life-cycle for hydrogen and gasoline as well as various other fuels were modeled using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in the Transportation Model (GREET 1.7). GREET is a spreadsheet model used to generate the life-cycle emission factors for various transportation fuels. GREET models present and future emissions as well as energy consumption. Emissions factors in units of g/mile of pollution and energy consumption in units of Btu/mile were generated for the full fuel life-cycle.



Source: (Argonne National Laboratory Presentation at the EPA's Fuel Cell Workshop Diagram June 27, 2001)

Figure 3.6.1 Schematic of the GREET Model's Inputs & Outputs

The GREET model provides emission factors in three categories: Feedstock, Fuel, and Vehicle Operation as seen in Figure 3.6.2. Emissions attributed during the Feedstock and Fuel portions of the life cycle were considered the "Well-to-Pump Stages." The Vehicle Operation portion of the life cycle was considered the "Pump-to-Wheel Stages."



Source: (Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies, Figure 1, ANL, 2001)

Figure 3.6.2 Life Cycle Stages in the GREET Model

Emissions factors were categorized by the GREET Model as Energy Consumption, Greenhouse Gases, or Criteria Pollutants as seen in Figure 3.6.3.

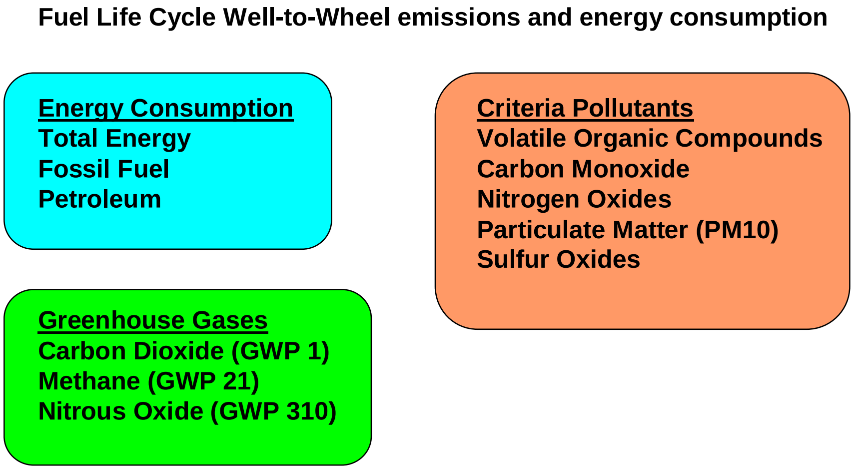


Figure 3.6.3 GREET Model Output

3.7 Two Model Approach

The MARKAL and GREET models were used in sequence to generate future light-duty transportation emission estimates for each of the scenarios. MARKAL provided realistic economic responses in the electric and transportation sectors due to hydrogen fuel and fuel cell vehicles penetrating the market. MARKAL provided the electric data to input into GREET for each of the scenarios. This study assumed 30% hydrogen fuel cell vehicles in 2030 leaving the remaining 70% of the light-duty transportation sector to be determined by the MARKAL model. MARKAL provided the breakdown of the remaining 70% by fuel and vehicle type. The GREET model provided output from various fuel pathways in terms of emission factors. Emission factors were provided for various fuel pathways in units of g/mile. Emissions were generated for future model year 2030 by combining GREET's emission factors, MARKAL's vehicle mix, and AEO's estimate of annual vehicles miles traveled.

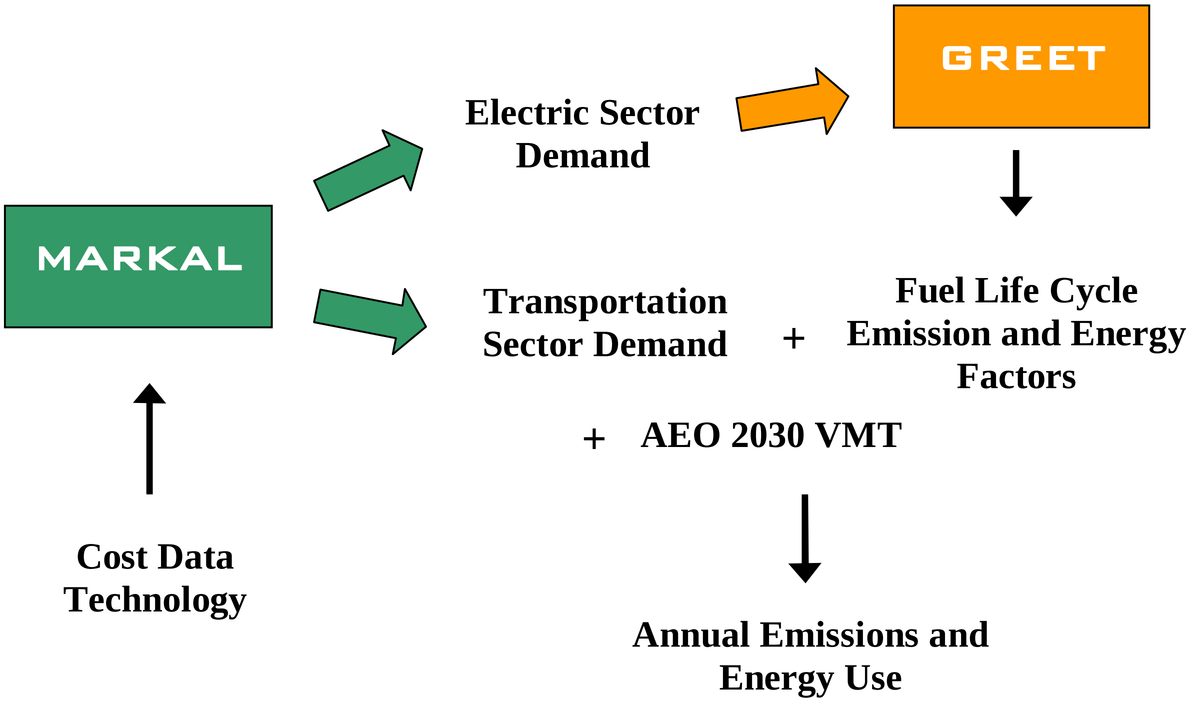


Figure 3.7.1 Flow Chart of Two-Model Approach

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Chapter 4

Future Fuel Life-Cycle Emissions Estimates

4.1 Numerical Results

Emissions estimates of the fuel life-cycles were generated for the U.S. light-duty vehicles in the year 2030. A list of key assumptions can be found in Table 4.1.1 below.

Table 4.1.1 Key Assumptions

Type of Gasoline: Reformulated Gasoline					
Type of Diesel: Low-Sulfur Diesel					
Feedstock source for Compressed Natural Gas, Liquefied Petroleum Gas, Liquefied Natural Gas: North American Natural Gas					
Gaseous Hydrogen for all scenarios					
Feedstock source for Hydrogen produced from natural gas: North American Natural Gas					
without CO2 sequestration					
No co-products					
MPG					
Gasoline Car	25.9				
Gasoline LDT1	19.62				
Gasoline LDT2	16.5				
Diesel Car MPG	40				
Diesel LDT1	31				
Diesel LDT2	19.8				
Gasoline HEV MPG	43.25				
Gasoline HEV LDT1	32.77				
Gasoline HEV LDT2	16.5				
H_2FCV MPG	62.72				
H_2FCV LDT1	48.66				
H_2FCV LDT2	16.5				
Central Plant H2 Production Efficiencies					
NG Feedstock	73.0%				
Coal Feedstock	63.0%				
Nuclear Energy	80.0%				
Urban LDV shares	62.2%				
Urban Shares of Electricity Generation:					
	Residual oil-fired power plants	Natural gas-fired power plants	Coal-fired power plants	Nuclear power plants	Biomass-fired power plants
Electricity Generation	39.0%	43.0%	16.0%	11.0%	0.0%

Table 4.1.2 List of Scenarios

Basecase
High Hybrid
Distributed Natural Gas
Thermochemical Nuclear
Distributed Electrolysis
Coal Gasification
Central Natural Gas

Table 4.1.3 lists the vehicle mix for each hydrogen scenario and the High Hybrid Scenario generated by MARKAL as well as the AEO 2006 Basecase estimates in 2030. Future estimates for vehicle mix included various vehicle technologies and fuels such as gasoline, diesel, compressed natural gas, liquefied petroleum gas, ethanol, and hydrogen. For example, MARKAL estimated the U.S. light-duty vehicle fleet to be composed of 13.2% moderate gasoline internal combustion engine (ICE) vehicles and 45.1% hybrid electric vehicles (HEV) in the Coal Gasification Scenario.

Table 4.1.3 Light-Duty Vehicle Mix in 2030

Scenario	Conv. Gasoline -ICE* Vehicles	Moderate Gasoline -ICE Vehicles	Hybrid Gasoline -Electric Vehicles	Diesel-ICE Vehicles	Compressed Natural Gas-ICE Vehicles	Electric Vehicles	Liquefied Petroleum Gas Vehicles	Ethanol Vehicles	H2 Fuel Cell Vehicles
Basecase	80.0%	0.0%	6.0%	5.0%	0.0%	0.0%	1.0%	7.0%	0.0%
High Hybrid	4.8%	12.1%	73.8%	3.9%	0.3%	0.1%	0.7%	4.3%	0.0%
Distributed Natural Gas	0.0%	14.8%	46.1%	3.9%	0.3%	0.1%	0.7%	4.2%	30.0%
Thermo-chemical Nuclear	4.8%	10.8%	45.1%	3.9%	0.3%	0.1%	0.7%	4.3%	30.0%
Distributed Electrolysis	1.5%	14.1%	45.1%	3.9%	0.3%	0.1%	0.7%	4.3%	30.0%
Coal Gasification	2.4%	13.2%	45.1%	3.9%	0.3%	0.1%	0.7%	4.3%	30.0%
Central Natural Gas	0.0%	9.5%	52.1%	3.3%	0.3%	0.1%	0.7%	4.0%	30.0%

* ICE = Internal Combustion Engine

A large change in one sector of the U.S. economy will have impacts on other sectors of the economy such as the electric sector. Similar to the vehicle mix, the electricity mix was determined using the MARKAL model. Table 4.1.4 lists the electricity mix for each hydrogen scenario and the High Hybrid Scenario generated by MARKAL as well as the AEO 2006 Basecase estimates in 2030. The electric sector was divided into five categories: residual oil, natural gas, coal, nuclear, biomass, and renewables. For example, MARKAL shows the U.S. to generate electricity from the following sources: 4.6% residual oil, 22.7% natural gas, 40.2% coal, 8.4% biomass, and 8.9% renewables for the hydrogen scenario produced from coal gasification.

Table 4.1.4 Electricity Mix in 2030

	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Renewables
Basecase	2.0%	12.2%	57.3%	16.9%	1.1%	10.4%
High Hybrid	3.3%	23.8%	43.8%	15.8%	4.2%	9.2%
Distributed Natural Gas	3.1%	12.0%	27.5%	28.8%	10.6%	18.0%
Thermo-chemical Nuclear	3.4%	24.1%	43.2%	15.0%	2.7%	11.5%
Distributed Electrolysis	3.3%	23.8%	43.8%	15.8%	4.2%	9.2%
Coal Gasification	4.6%	22.7%	40.2%	15.2%	8.4%	8.9%
Central Natural Gas	4.3%	23.3%	42.6%	15.1%	5.9%	8.9%

The emissions results as well as energy consumption for the light-duty vehicle fuel life-cycles in the U.S. are presented in Table 4.1.5. The categories of output are reflective of the results generated by the GREET model. The U.S. light-duty transportation annual emissions were obtained by combining the total vehicle miles traveled ($4x10^{12}$ miles) and the emission factors (in grams/mile) generated by the GREET model for each vehicle fuel and technology combination. Emission and energy factors could be compared on a unit basis by dividing annual emission results by U.S. annual vehicle miles traveled. Total energy emission factors were generated by the GREET model in units of Btu/mile. The total energy, the amount consumed from fossil fuels, and the amount consumed from petroleum were generated as well. Emission factors are generated by the GREET model in three categories: Greenhouse Gases, Total Criteria Pollutants, and Urban Criteria Pollutants. Greenhouse gas emission factors included carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The overall greenhouse gas category was determined using the CO_2-equivalent for the three greenhouse gases estimated. The global warming potential for methane and nitrous oxide is

21 and 310 times that of carbon dioxide. The criteria pollutant emission factors were generated by the GREET model and included volatile organic compounds (VOC), carbon monoxide (CO), nitrous oxides (NOx), particulate patter less than 10 microns (PM_{10}), and sulfur oxides (SOx). Total criteria pollutants were generated as well as the portion of the total that would be emitted in urban areas. The urban criteria pollutant category is an important distinction since air pollutants that affect human health are a concern where the air pollution is concentrated, mainly in urban areas.

Table 4.1.5 Fuel Life Cycle Emissions and Energy Consumption in 2030

	Basecase	High Hybrid	Distributed Natural Gas (SMR)	Thermo-chemical Nuclear	Distributed Electrolysis	Coal Gasification	Central Natural Gas (SMR)
Item	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**
Total Energy	25,710,672	18,360,965	22,983,209	16,482,755	22,263,077	18,139,480	17,761,119
Fossil Fuels	23,584,237	17,144,330	16,859,858	12,527,083	19,615,418	16,949,060	16,597,128
Petroleum	19,829,498	14,672,216	7,629,553	10,153,668	11,799,257	10,603,258	10,588,515
Item	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**
CO2	1,977,790	1,435,151	1,355,022	1,062,833	1,894,951	1,597,760	1,343,785
CH4	2,517	1,808	2,632	1,355	2,286	1,913	1,913
N2O	184	127	382	100	117	101	102
GHGs	2,088,408	1,514,263	1,528,769	1,123,468	1,982,249	1,671,671	1,417,890
VOC: Total	1,368	1,041	974	723	750	794	782
CO: Total	16,147	14,532	11,624	11,353	9,153	11,511	11,554
NOx: Total	1,539	1,126	1,543	894	1,845	939	1,052
PM10: Total	464	333	605	335	1,223	1,081	373
SOx: Total	660	426	693	393	1,557	458	442
VOC: Urban	805	614	489	420	401	440	442
CO: Urban	9,905	8,915	6,997	6,977	5,520	7,063	7,072
NOx: Urban	518	402	320	287	512	306	326
PM10: Urban	126	105	115	91	118	93	102
SOx: Urban	203	132	94	106	325	109	110

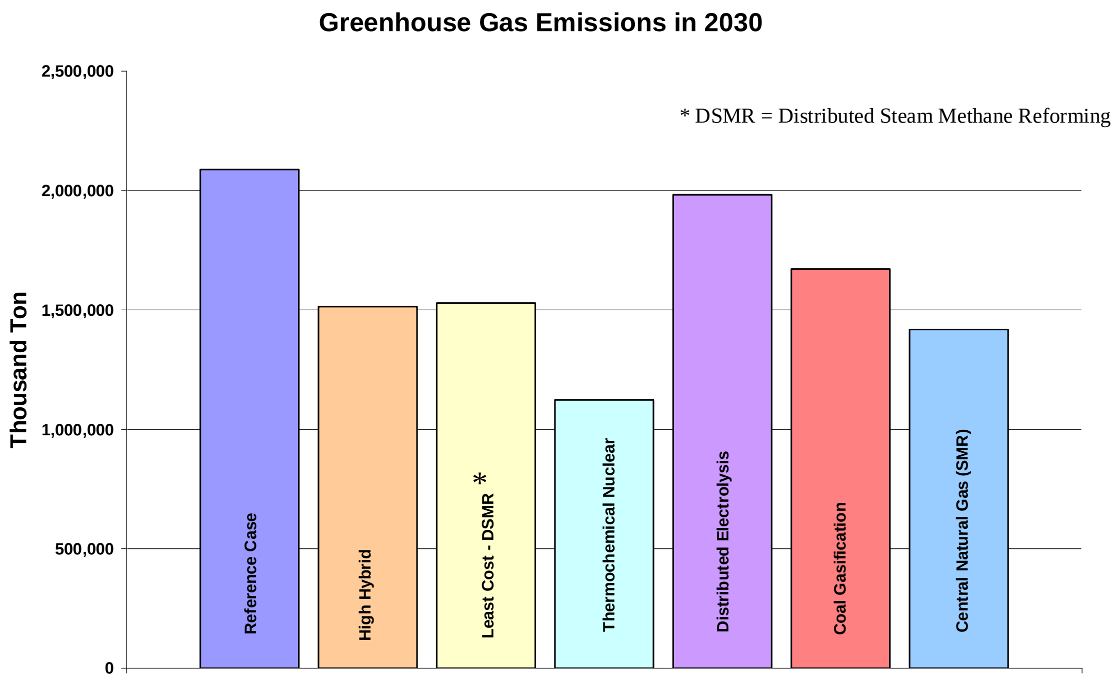
Numerical results in units of percentage change for each scenario from the AEO 2006 Basecase are presented in Table 4.1.6.

Table 4.1.6 Percentage Changes from Basecase Scenario in 2030

	Basecase	High Hybrid	Least Cost - DSMR	Thermo-chemical Nuclear	Distributed Electrolysis	Coal Gasification	Central Natural Gas (SMR)
Item	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**	**Energy (billion Btu)**
Total Energy	0%	-29%	-11%	-36%	-13%	-29%	-31%
Fossil Fuels	0%	-27%	-29%	-47%	-17%	-28%	-30%
Petroleum	0%	-26%	-62%	-49%	-40%	-47%	-47%
Item	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**	**Emissions (thousand tons)**
CO2	0%	-27%	-31%	-46%	-4%	-19%	-32%
CH4	0%	-28%	5%	-46%	-9%	-24%	-24%
N2O	0%	-31%	108%	-46%	-36%	-45%	-45%
GHGs	0%	-27%	-27%	-46%	-5%	-20%	-32%
VOC: Total	0%	-24%	-29%	-47%	-45%	-42%	-43%
CO: Total	0%	-10%	-28%	-30%	-43%	-29%	-28%
NOx: Total	0%	-27%	0%	-42%	20%	-39%	-32%
PM10: Total	0%	-28%	30%	-28%	164%	133%	-20%
SOx: Total	0%	-35%	5%	-41%	136%	-31%	-33%
VOC: Urban	0%	-24%	-39%	-48%	-50%	-45%	-45%
CO: Urban	0%	-10%	-29%	-30%	-44%	-29%	-29%
NOx: Urban	0%	-22%	-38%	-45%	-1%	-41%	-37%
PM10: Urban	0%	-17%	-8%	-28%	-6%	-26%	-19%
SOx: Urban	0%	-35%	-54%	-48%	60%	-46%	-46%

4.2 Graphical Results

Graphical results of the annual emissions for greenhouse gases and total criteria pollutants are presented in Figures 4.2.1 through 4.2.13.



* DSMR = Distributed Steam Methane Reforming

Figure 4.2.1 Greenhouse Gas Emissions for Various Hydrogen Production Pathways in 2030

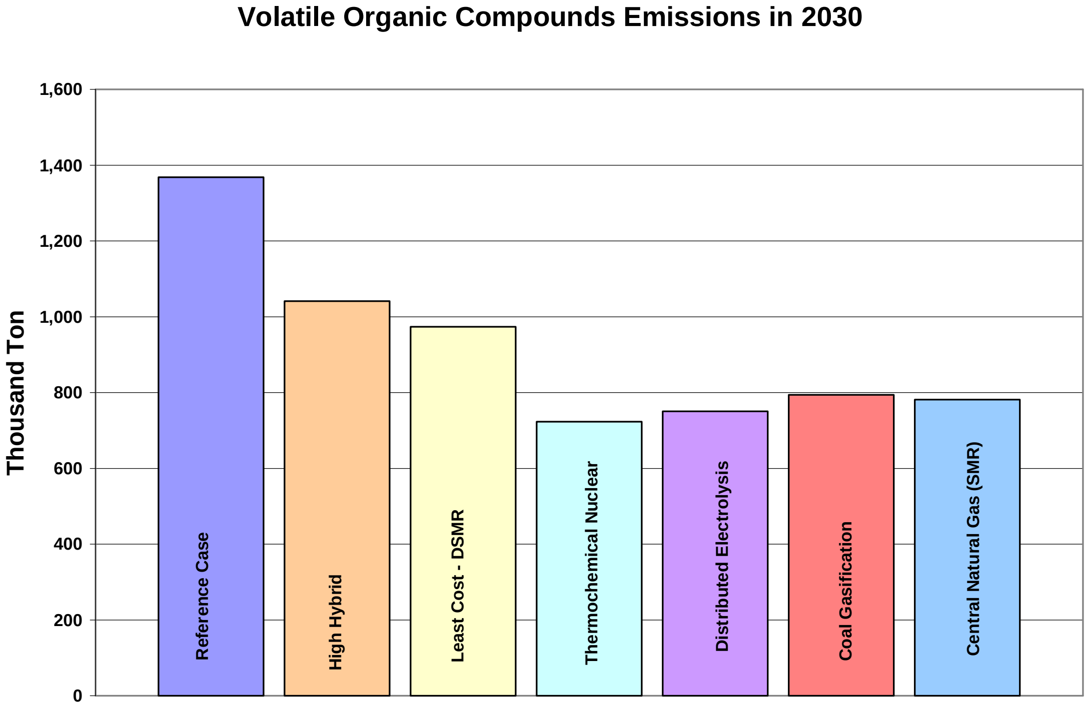


Figure 4.2.2 Volatile Organic Compound Emissions for Various Hydrogen Production Pathways in 2030

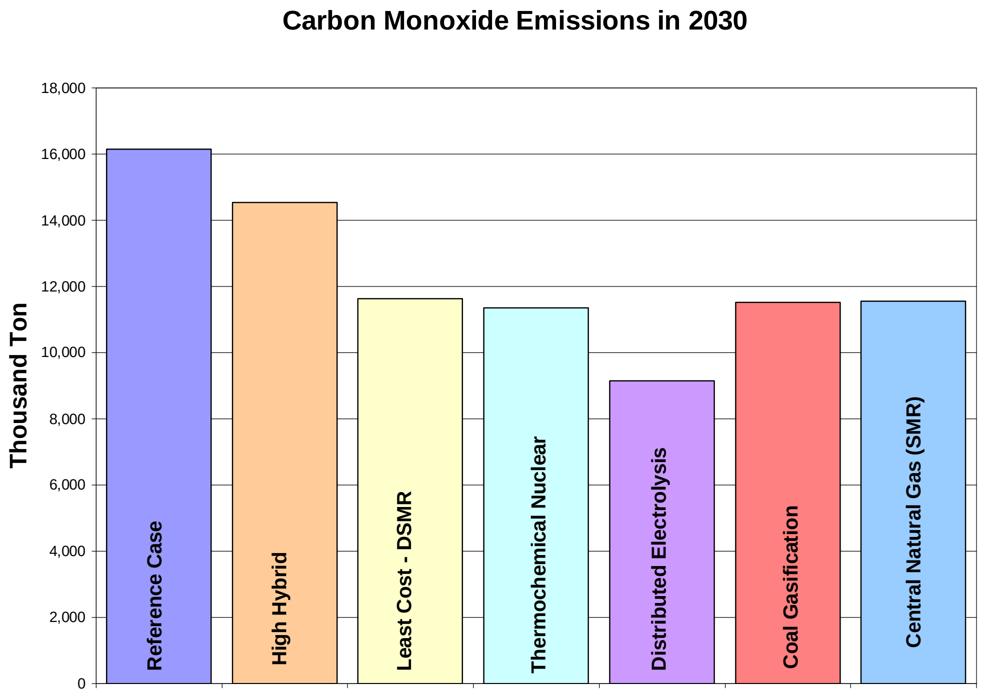


Figure 4.2.3 Carbon Monoxide Emissions for Various Hydrogen Production Pathways in 2030

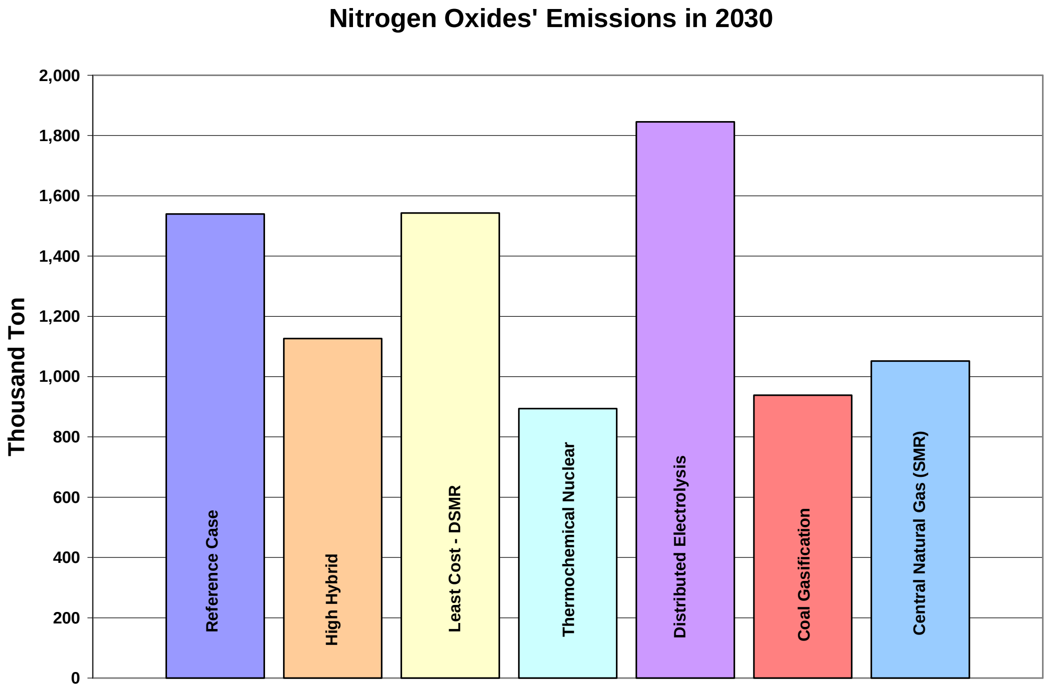


Figure 4.2.4 Nitrogen Oxides' Emissions for Various Hydrogen Production Pathways in 2030

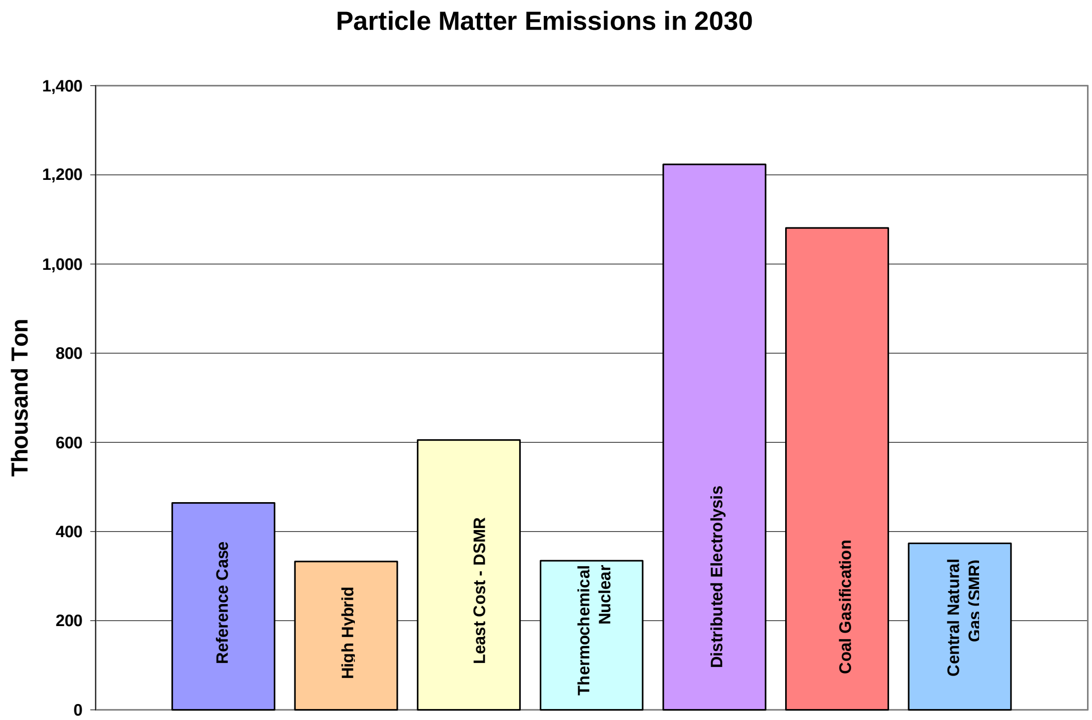


Figure 4.2.5 Particle Matter Emissions for Various Hydrogen Production Pathways in 2030

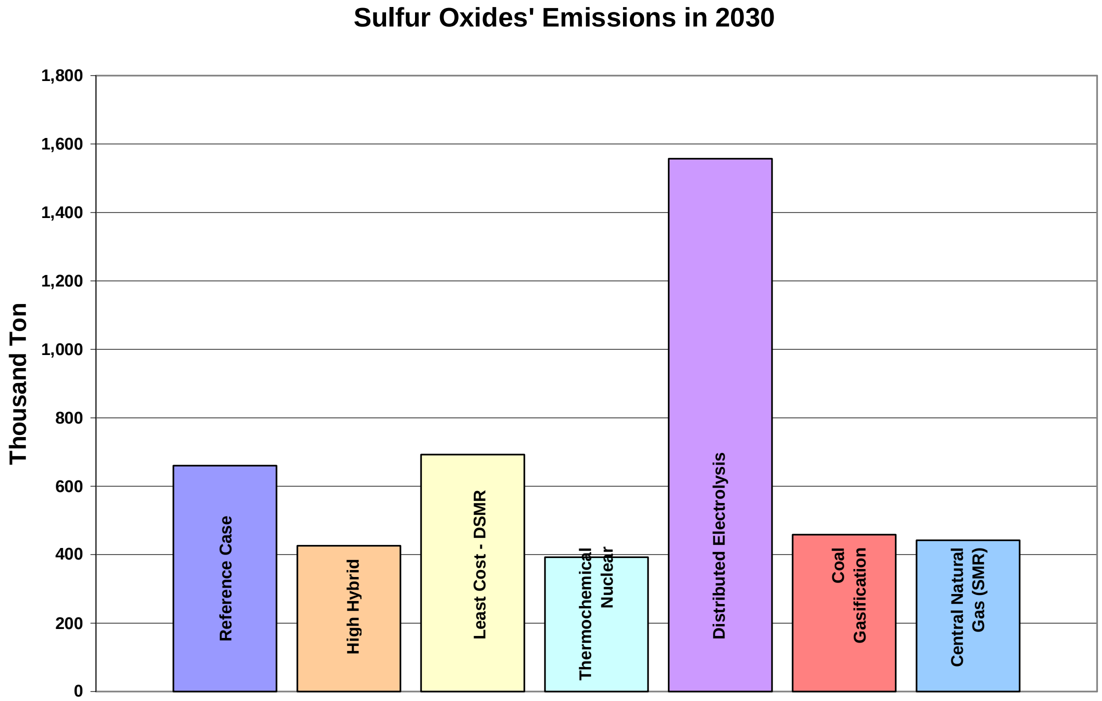


Figure 4.2.6 Sulfur Oxides' Emissions for Various Hydrogen Production Pathways in 2030

The percentage changes for each scenario from the AEO 2006 Basecase Scenario are presented in figures 4.2.7 through 4.2.13 for total criteria pollutant and greenhouse gas emissions.

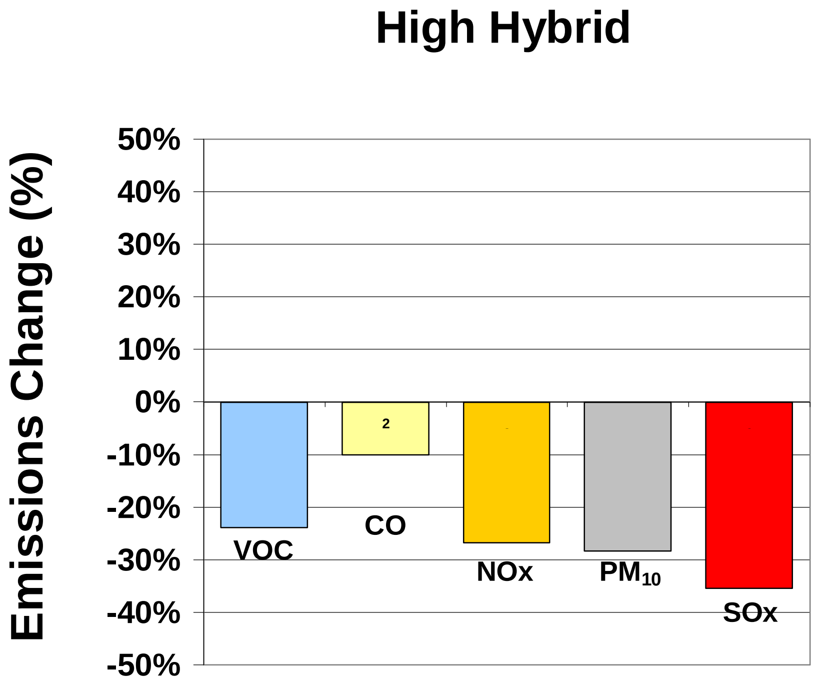


Figure 4.2.7 High Hybrid Scenario Emissions Changes Basecase in 2030

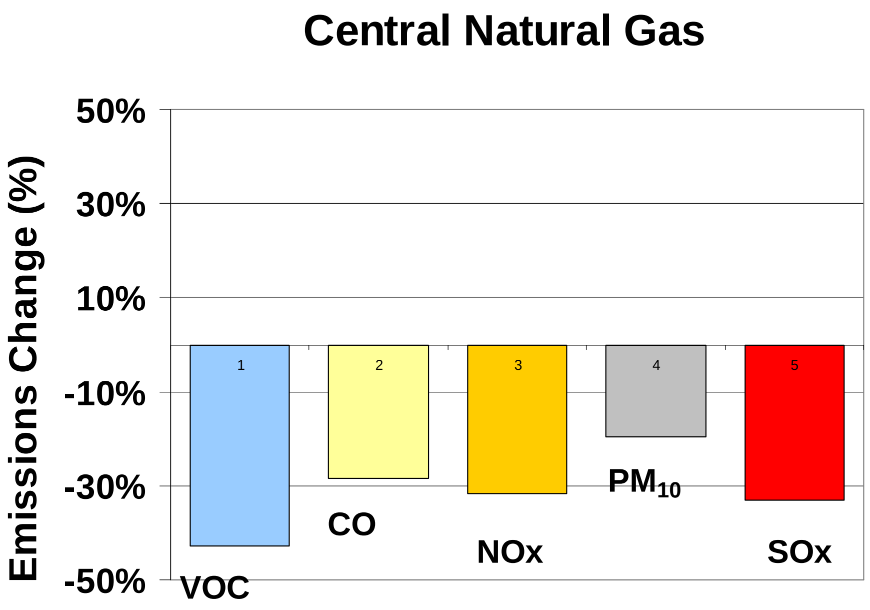


Figure 4.2.8 High Hybrid Scenario Emissions Changes Basecase in 2030

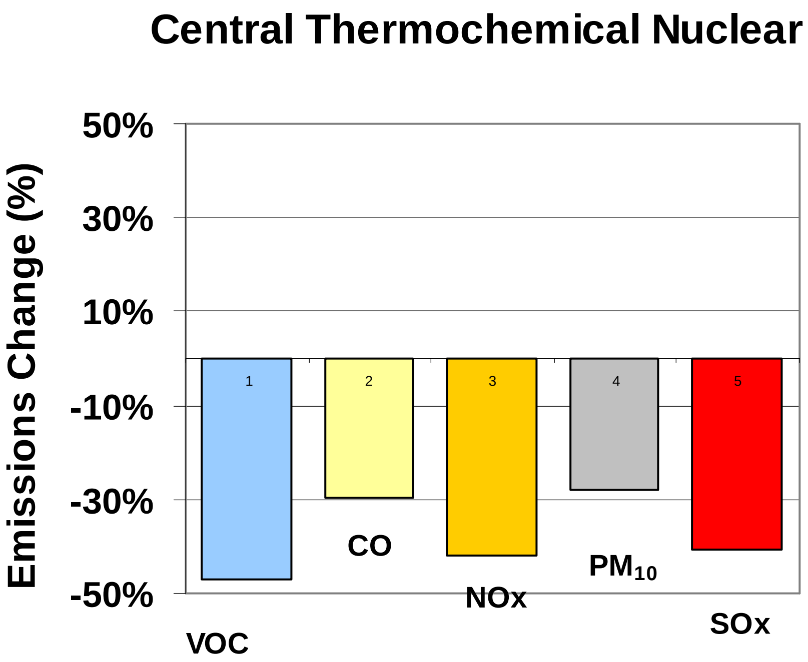


Figure 4.2.9 Central Thermochemical Nuclear Scenario
Emissions Changes from Basecase in 2030

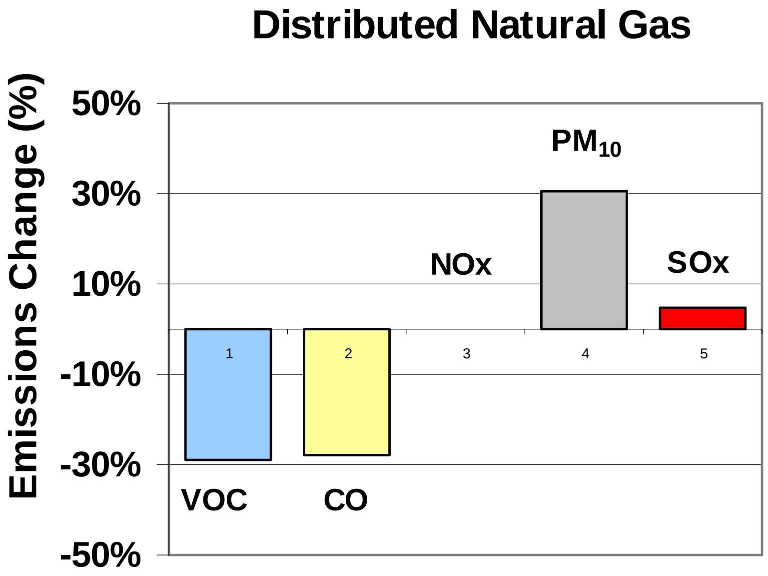


Figure 4.2.10 Distributed Natural Gas Scenario Emissions Changes from Basecase in 2030

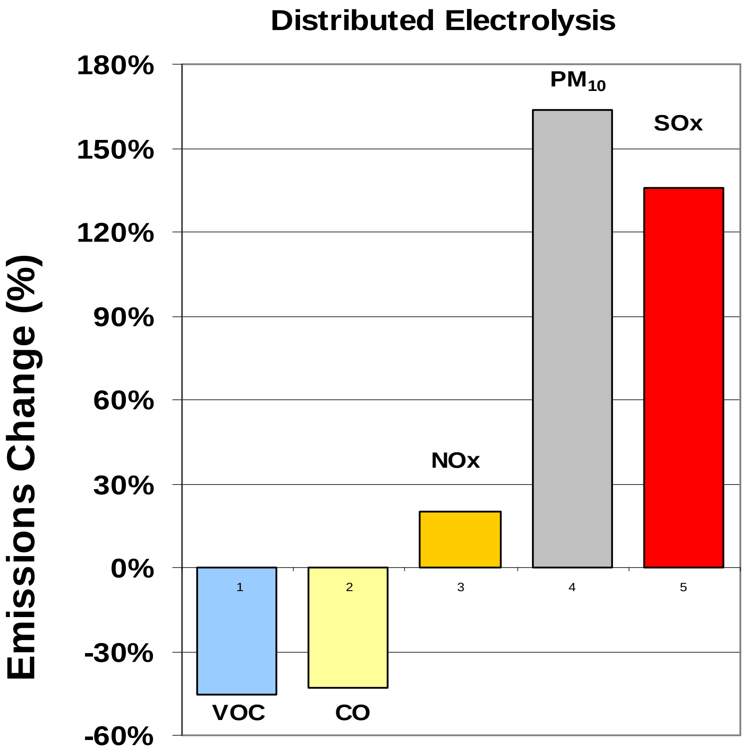


Figure 4.2.11 Distributed Electrolysis Scenario Emissions Changes from Basecase in 2030

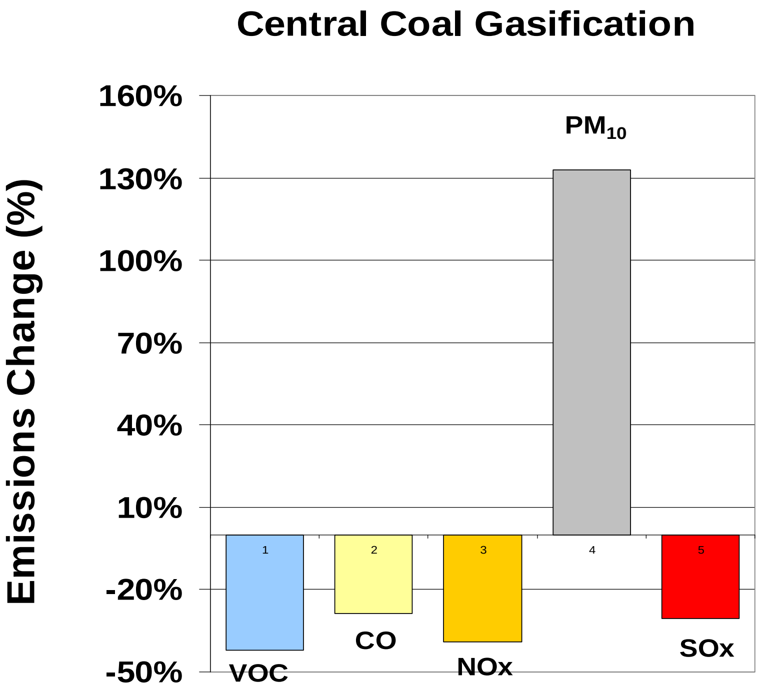


Figure 4.2.12 Central Coal Gasification Scenario
Emissions Changes from Basecase in 2030

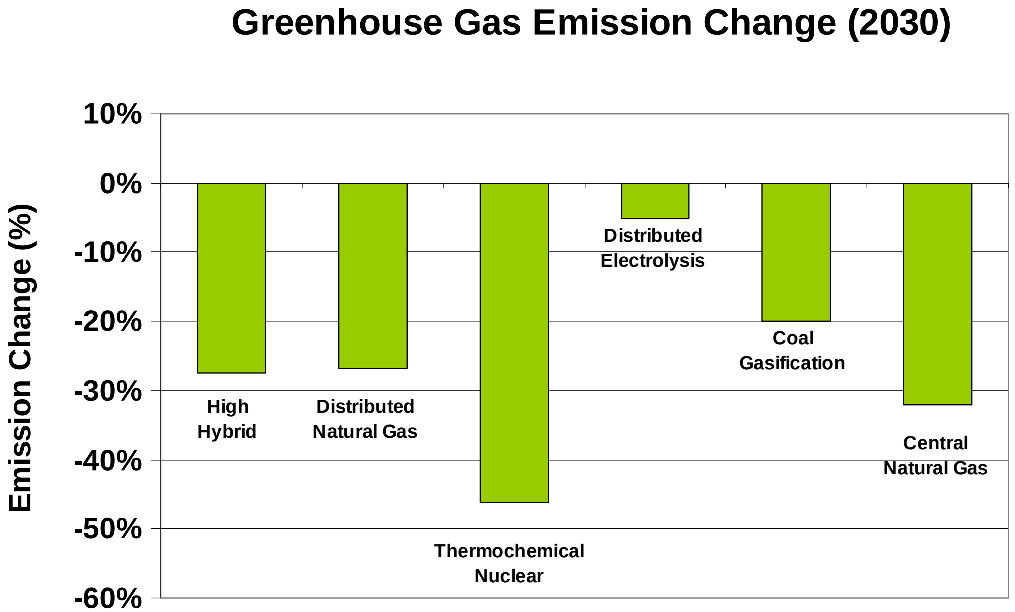


Figure 4.2.13 Greenhouse Gas Emission Changes from Basecase Scenario
for Various Hydrogen Production Scenarios in 2030

Chapter 5

Discussion of Results: Will Hydrogen Fuel Overall Increase or Decrease Emissions?

5.1 Overview of Results

When comparing emissions for each of the scenarios modeled in the study it is important to remember that overall changes due to transportation fuel production are a result of multiple changes that occurred in the vehicle mix and the electricity mix. In model year 2030, hydrogen fuel cell vehicles were set at 30% of the vehicle mix while the remaining inputs were allowed to optimally adjust based on cost to determine the breakdown of the overall vehicle mix and electric mix. One objective of this study was to determine how hydrogen fuel would affect fuel life-cycle emissions by using an economic model that would provide scenario inputs for emissions generation. The results therefore reflect not only changes from hydrogen fuel cell vehicle penetration, but also from other changes in the vehicle mix and electricity mix. The effects of the electric sector on each scenario depend on the amount of electricity each hydrogen production technology demands. All scenarios use electricity in the various fuel production processes but in various amounts. For example, hydrogen production using electrolysis requires a large electricity demand, and therefore is impacted more by changes in the electric sector as compared to other hydrogen production scenarios. In general, the results are reflective a hundreds of assumptions such as fuel costs, emission factors, and efficiencies that include a large degree of uncertainty for future year 2030. The basecase selected also includes some degree of uncertainty and would effect emission changes. The High Hybrid Scenario could have been used as a more progressive basecase where the future vehicle fleet in year 2030 in made up of 74% hybrid-electric vehicles.

5.1.1 Greenhouse Gas Emissions

All scenarios reduced greenhouse gas emissions in future year 2030 when compared to the Basecase. The Thermochemical Nuclear Scenario resulted in the most reduction of greenhouse gas emissions with a 46% reduction from the Basecase as seen in Figure 4.2.13. Emission reductions can be attributed to the thermochemical nuclear technology used to produce hydrogen as well as increases in hybrid-electric vehicles and moderate gasoline ICE vehicles. The Distributed Electrolysis Scenario resulted in the least reduction of greenhouse gas emissions with a 5% reduction from the Basecase as seen in Figure 4.2.13. When evaluating the full fuel life-cycle, the task on pinpointing the portion or portions of the fuel life-cycle that cause emissions increases or decreases cannot be determined without a detailed analysis of each step involved in the fuel life cycle.

5.1.2 Total Criteria Pollutant Emissions

Overall volatile organic compound and carbon monoxide emissions were reduced in every scenario when compared to the Basecase. Nitrogen oxides' emissions generated no change in the Distributed Natural Gas Scenario and a 20% increase in the Distributed Electrolysis Scenario. One reason for the increase in nitrogen oxides is the increase in biomass energy (10.6%) used in the electric sector. Particulate matter emissions were increased in the Distributed Natural Gas Scenario (30%), the Distributed Electrolysis Scenario (164%), and the Coal Gasification Scenario (133%). These increases can be attributed to the production process of hydrogen, electricity generation, and the mining and processing of the primary fuel source. Sulfur oxides emissions were increased from the Basecase in the Distributed Natural Gas Scenario (5%) and the Distributed Electrolysis Scenario (136%) mainly from the increased demand for electricity from coal plants.

5.1.3 Urban Criteria Pollutant Emissions

Emissions reductions occurred in all five categories of criteria pollutants in urban areas for every scenario when compared to the Basecase with the exception of Distributed Electrolysis. The Distributed Electrolysis Scenario increased sulfur oxide emissions in urban areas by 60%. This large increase can be attributed to increase in coal-fired power plant emissions.

5.2 Other Methods of Hydrogen Production

The hydrogen scenarios modeled in the study represent only some of the options for production of hydrogen. Out of the five hydrogen scenarios modeled in this study, four are thermal scenarios and one is electrolytic. Hydrogen could also have been modeled using photolytic processes that harness the sun's energy. If the production of hydrogen using electrolysis combined with cleaner sources of electric energy such as renewable energy were considered, the fuel life-cycle of hydrogen would virtually produce zero emissions. Hydrogen fuel is only as clean as the resources and energy used to produce it. There are also additional options for the feedstock fuel used in steam methane reforming. This study assumed natural gas as feedstock in SMR but fuels such as methanol or ethanol could also be used to extract hydrogen as well.

5.3 References Cited

[1] "Distributed Hydrogen Production via Steam Methane Reforming." U.S. Department of Energy: Hydrogen Program. 12 Jul. 2006. 21 Mar. 2008. <http://www.hydrogen.energy.gov/docs/cs_distr_steam_methane_reform.doc>.

[2] "Getting Along without Gasoline – The Move to Hydrogen Fuel." Lawrence Livermore's National Laboratory. March 2006. 29 Mar. 2008. <http://www.llnl.gov/str/pdfs/03_96.3.pdf>.

Chapter 6

Hydrogen Fuel and the Future Research

6.1 Best Hydrogen Production Method

Overall, the hydrogen scenario providing the most reduction in emissions and energy use is the Central Thermochemical Nuclear Scenario compared to Basecase. Energy usage decreased by 36%, greenhouse gas emissions decreased by 9.6×10^8 tons, and criteria emissions were reduced by 28-47%. The emissions and energy consumption varied by scenario. The scenarios were ranked from greatest to least benefit in Table 6.1.1. and Table 6.1.2.

Table 6.1.1 Greatest Benefit Ranking of Energy Usage Compared to Basecase

1, Central Thermochemical Nuclear
2. Central Natural Gas
3. High Hybrid & Central Coal Gasification
4. Distributed Electrolysis
5. Distributed Natural Gas

Table 6.1.2 Greatest Benefit Ranking of Greenhouse Gas Emissions Compared to Basecase

1, Central Thermochemical Nuclear
2. Central Natural Gas
3. High Hybrid & Distributed Natural Gas
4. Central Coal Gasification
5. Distributed Electrolysis

Based on this study, in terms of climate change emissions and energy usage, the only two hydrogen scenarios that proved to be more beneficial than the High Hybrid Scenario are Central Thermochemical Nuclear and Central Natural Gas.

For the criteria pollutants, the more beneficial scenario was not as clear, but varied for each scenario by specific pollutant and location, i.e. urban criteria pollutant emissions. All hydrogen scenarios reduce VOC, both total and urban, compared to the High Hybrid Scenario. Carbon monoxide emissions, both total and urban, are reduced in all of the hydrogen scenarios. For nitrogen oxide, particulate matter, and sulfur oxide emissions, the results varied widely among hydrogen scenarios. Reductions in NOx and SOx emissions were obtained for Central Thermochemical Nuclear, Central Coal Gasification, and Central Natural Gas. NOx and SOx emissions had either no net change or an increase for the Distributed Natural Gas and Distributed Electrolysis Scenarios. Overall, the results generated for the Distributed Natural Gas Scenario have the least benefit of all the scenarios. Distributed Natural Gas is the only hydrogen scenario to have an increase in an urban criteria pollutant, with a 60% increase in urban SOx. In general, however, all the hydrogen scenarios reduced urban criteria pollutant emission more than the High Hybrid emissions due elimination of tailpipe emissions in FCVs.

6.2 Future Research

Further research is needed to include the entire electric sector emissions for each hydrogen scenario to generate economy-wide emissions changes. This study only included emissions from the electric sector that are required to extract, produce, store, and distribute the fuel needed in the transportation sector. Electric demand from the residential and commercial sectors were not included but would have a greater impact either positively or negatively depending on how hydrogen fuel affected the electric mix. Hydrogen scenarios that directly use renewable energy to produce hydrogen should also be considered since these scenarios could have the potential for an emissions-free hydrogen fuel life-cycle.

A follow-up to this study could be performed to determine specifically where emissions are generated within each fuel life-cycle. Other forms of pollution, such as water pollution, should be considered for each scenario for a complete analysis of environmental issues. Also, building the infrastructure required for each scenario and the associated environmental and economic costs also needed to be considered in evaluating future scenarios.