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The Advanced Energy Initiative

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Abstract

The President's Advanced Energy Initiative (AEI), launched in 2006, addresses the challenges of energy supply and demand facing our Nation by supporting research and development of advanced technologies for transportation and stationary power generation. The AEI portfolio includes clean coal, nuclear and renewable energy technologies (solar and wind) for stationary power generation and advanced battery technologies, cellulosic ethanol as a fuel and hydrogen fuel cells for transportation. These research and development programs are underpinned by comprehensive life-cycle analysis efforts using models such as Hydrogen Analysis (H2A) and Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) to enable a better understanding of the characteristics and trade-offs associated with advanced energy options and to help decision makers choose viable pathways for clean, reliable and affordable energy.

Keywords: Advanced Energy Initiative; Hydrogen; Fuel cells; Transportation

1. Introduction

Energy supply and demand in the U.S. has been transformed over the last century, especially after the 1950s [1]. Subsequent to an extended period when wood was the main source of energy, coal was introduced in 1850. Petroleum and natural gas entered the picture in the beginning of the 20th century and became more prominent by the middle of the century. By the end of the 20th century, both fossil and renewable sources of energy played varying roles in the U.S. energy picture. While the portfolio of options has expanded, factors such as increased dependence on fossil resources, changes in trends of energy use, environmental damage, geo-political concerns, resource limitations and a very fast-paced consumption rate have introduced many challenges.

The President's Advanced Energy Initiative (AEI), launched in the beginning of 2006, addresses the challenges in both transportation and power generation and involves a broad portfolio of basic and applied research and technology development for near-, mid- and long-term approaches [2]. The AEI provides a 22% increase in funding for research involving clean energy technologies at the Department of Energy (DOE), subject to Congressional appropriations. This funding will be valuable in leveraging the talent and innovation of the nation's scientists and engineers in overcoming the barriers and clearing a path to clean, reliable and affordable energy.

This paper describes the components of the AEI and the energy challenges and solutions related to them. Section 2 sets the context by giving a general overview of energy in the U.S. Section 3 follows with a more detailed look at the AEI and its elements. As transportation is a major factor in our dependence on foreign oil and our environmental issues and Section 4 provides the results of well-to-wheels analyses.

2. U.S. energy overview

2.1. Energy production and consumption

The U.S. is not self-sufficient in terms of energy. In the latter part of the 1950s, consumption of energy outpaced what was being produced domestically (Fig. 1). Subsequently, the U.S. became a net importer of energy and imports have escalated at a significant rate since 1985. Energy is primarily consumed by

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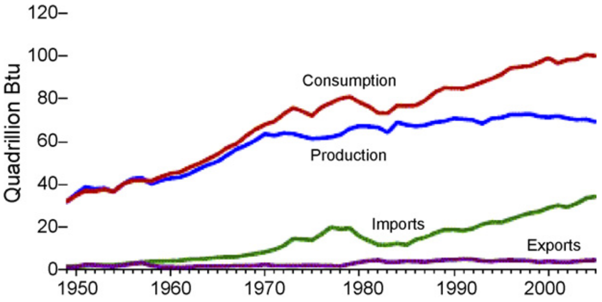
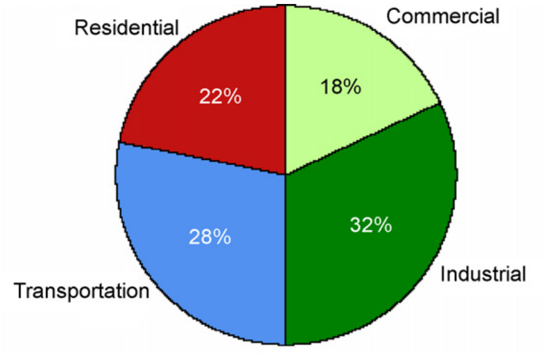


Source: Energy Information Administration (EIA), Annual Energy Review, DOE/EIA-0384(2005),
National Energy Information Center, Washington, D.C., July 27, 2006, pp. 4.

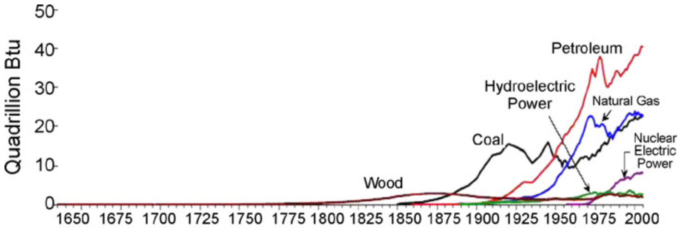
Fig. 1. Overview of energy in the U.S.



Source: Energy Information Administration (EIA), Annual Energy Review,
DOE/EIA-0384(2005),
National Energy Information Center, Washington, D.C.,
July 27, 2006, pp. 36.

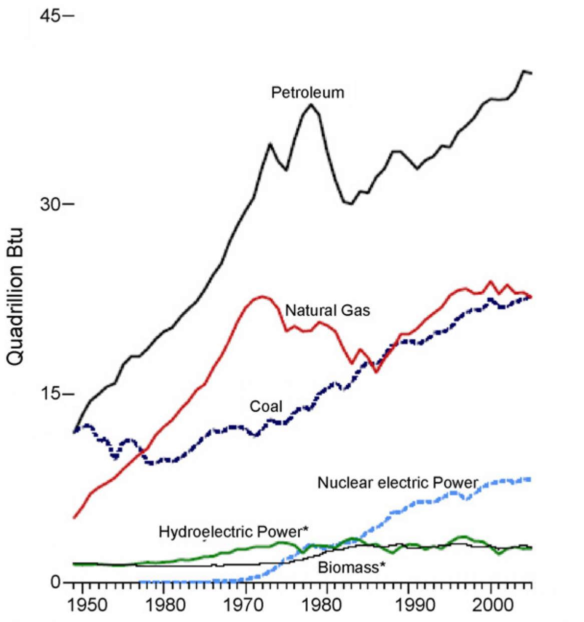
Fig. 2. End-use sector shares of total energy use in the U.S., 2005.

the industrial and transportation sectors, followed by the residential and commercial sectors (Fig. 2). History reveals that wood was a major resource in previous centuries, the U.S. began to diversify in 1850 with the introduction of coal and the subsequent emergence of petroleum and natural gas use (Fig. 3). Between 1950 and 1960, use of coal dropped slightly, while petroleum and natural gas use increased (Fig. 4). All fossil resources saw increasing consumption by 1960, while hydroelectric and biomass use emerged. Nuclear power came into play in the 1970s and steadily increased, before stabilizing at the beginning of the 21st century.



Source: Energy Information Administration (EIA), Annual Energy Review, DOE/EIA-0384(2005),
National Energy Information Center, Washington, D.C., July 27, 2006.

Fig. 3. Historical perspective of resource use for energy in the U.S.



Source: Energy Information Administration (EIA), Annual Energy Review,
DOE/EIA-0384(2005),
National Energy Information Center, Washington, D.C., July 27, 2006, pp. 8.

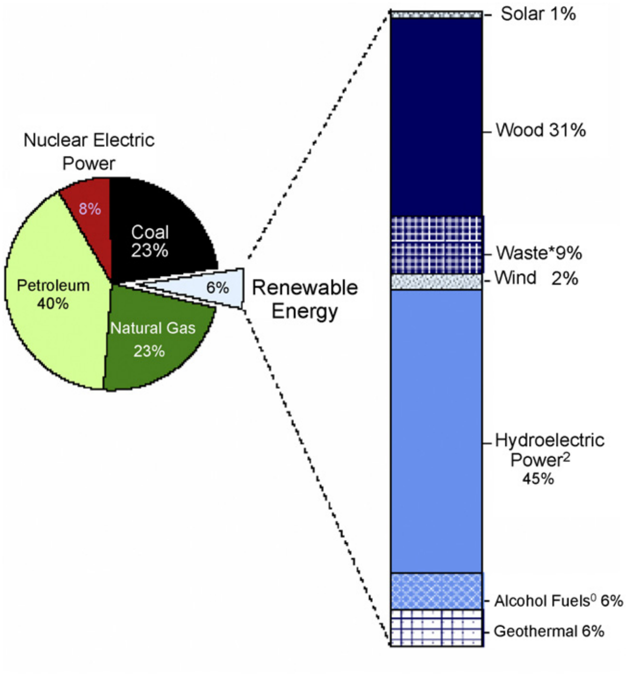
Fig. 4. Energy consumption in the U.S. by major source, 1949–2005.

While the use of renewable resources increased throughout the years, it has done so at a lower rate and quantity than fossil fuels. Currently, renewable energy accounts for 6% of overall energy use [1], with hydroelectric power making up the majority (Fig. 5). Projections of trends in U.S. energy use indicate that reliance on fossil resources will continue to grow, with a modest expansion in renewables expected and use of nuclear resources staying relatively stable (Fig. 6).

The environmental implications of energy use give rise to important considerations. Fig. 7 displays the carbon dioxide emissions from each sector of the economy. The transportation sector has become the largest contributor of carbon dioxide emissions, reaching 1.9 million metric tonnes in 2004 [1].

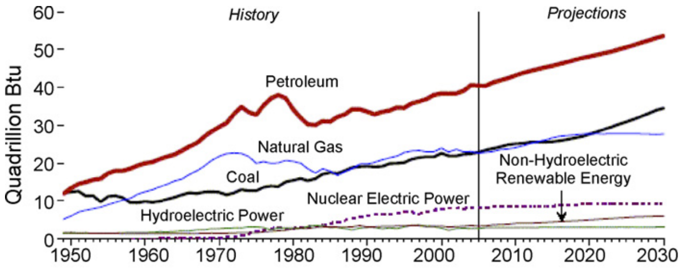
2.2. Electricity generation and consumption

The U.S. electricity sector faces several challenges. Events of the past few years have highlighted the susceptibility of the electricity grid and the pipeline network to both natural and man-made supply disruptions. Additionally, the environmental impacts of electricity generation continue to be an issue, especially with increasing energy demand (Fig. 8). The U.S. electricity sector is mainly dependent on fossil fuels, which account for 70% of the resources used, with coal supplying half of the generation and natural gas supplying 18% (Fig. 9) [1]. Another significant contributor is nuclear power at 20% [1], but this sub-sector has remained relatively constant since the capacity increases observed in the early 1970s. Renewable energy accounts for 9% of the electricity sector [1]. Hydropower and biomass are the major players, accounting for approximately 75% and 17% of electricity generation, respectively [1].



Source: Energy Information Administration (EIA), Annual Energy Review, DOE/EIA-0384(2005), National Energy Information Center, Washington, D.C., July 27, 2006, pp. 280.

Fig. 5. Renewable energy in the U.S. as share of total energy, 2005.

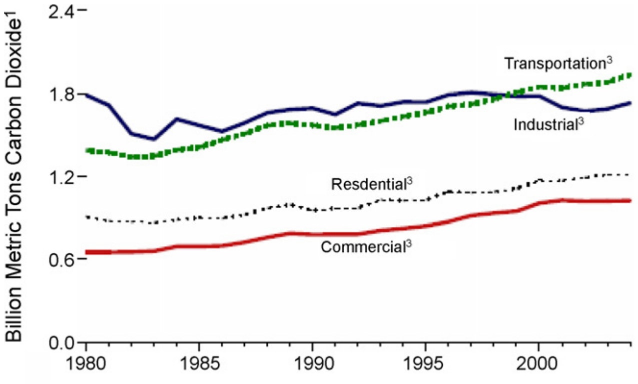


Source: Energy Information Administration (EIA), Annual Energy Review, DOE/EIA-0384(2005), National Energy Information Center, Washington, D.C., July 27, 2006, pp. xx.

Fig. 6. Past U.S. energy trends and projections to 2030.

Petroleum is the least consumed resource in the electricity sector (3%) [1] but plays a significant role in the transportation sector, as described in Section 2.3.

Natural gas demand in the U.S. has risen considerably, from 4.2% in 1986 to 15.9% in 2005 [1], and is mainly provided by pipelines from Canada. A smaller portion of the demand is met from Trinidad & Tobago, Algeria and other countries,[1] mostly in the form of liquefied natural gas. The natural gas market exhibits a tight balance between supply and demand, making it more susceptible to adverse natural and geopolitical incidents. This was seen in 2006 when natural gas prices increased from approximately US$ 3 per thousand cubic feet to over US$ 8 per thousand cubic feet following Hurricanes Katrina and Rita [2]. The volatility of natural gas prices has also had a significant impact on the U.S. industrial sector. The National Association of Manufacturers has indicated that the chemicals and plastics industries have suffered losses of 250,000 jobs and US$ 65 billion in business due to increasing natural gas prices [3].



Source: Energy Information Administration (EIA), Annual Energy Review, DOE/EIA-0384(2005), National Energy Information Center, Washington, D.C., July 27, 2006, pp. 340.

Fig. 7. Carbon dioxide emissions by end-use sector, 1980–2004.

2.3. *Transportation energy use*

The U.S. produces 9.1% of the world's petroleum, but consumes 24.9% of what is produced globally [4]. With consumption outpacing domestic production, U.S. oil imports continue to increase—oil accounts for approximately 90% of net U.S. energy imports. Approximately, 67% of oil use in the U.S. is for transportation. Currently, 60% of the oil is imported, and that is projected to increase to 68% if business as usual is continued [5]. Fig. 10 demonstrates the gap between oil use for various transportation applications and domestic production. Prior to the 1990s, domestic oil production was able to supply the transportation demand; however, the gap has been widening since then and is expected to broaden substantially.

3. The Advanced Energy Initiative

The Advanced Energy Initiative [2] addresses issues related to the two major and critical components of the energy sector—transportation and stationary power generation. The research needs, challenges and future prospects related to these two areas are described in more detail in Sections 3.1 and 3.2.

3.1. *Stationary power generation*

The AEI seeks to diversify and enhance the resources used in electricity generation to lessen the impact of volatile resources, reduce harmful environmental impacts and provide a more reliable and sustainable resource base. This is envisioned through the development of advanced technologies for clean coal, expansion of nuclear energy and the deployment of renewable technologies such as solar and wind energy.

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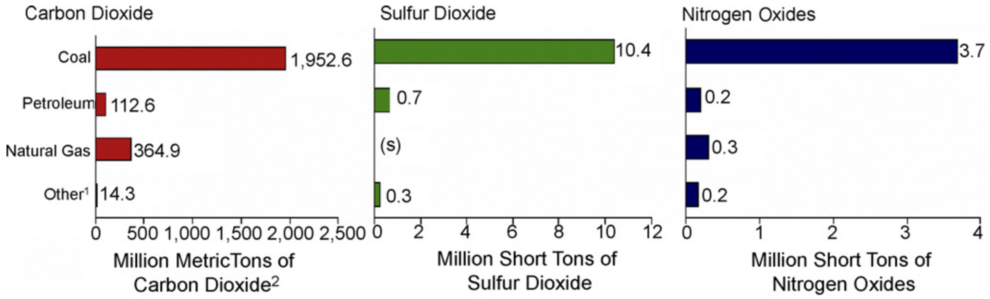
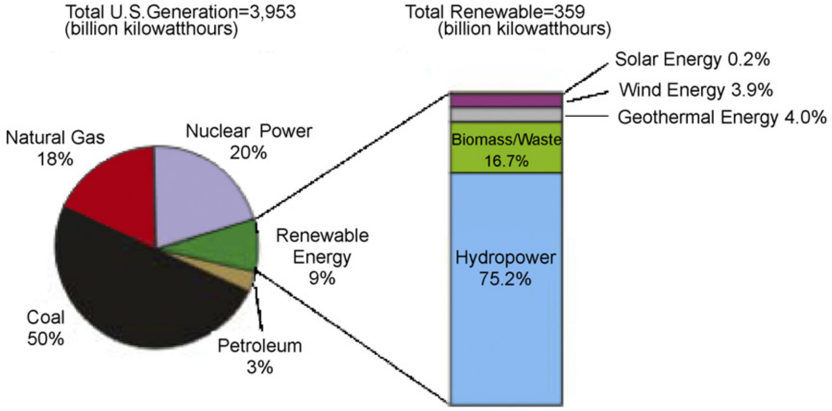
[1] Egypt, Malaysia, Nigeria, Qatar, Oman and Mexico.



Source: Energy Information Administration (EIA), Annual Energy Review, DOE/EIA-0384(2005), National Energy Information Center, Washington, D.C., July 27, 2006, pp. 350.

Fig. 8. Emissions from the electricity sector by type of generating unit, 2004.



Source: Energy Information Administration (EIA) Brochure, Renewable Energy Sources: A Consumer's Guide, National Energy Information Center, Washington, D.C., 2004.

Fig. 9. Electricity generation by energy source, 2004.

3.1.1. *Clean coal technologies*

The U.S. contains very large recoverable coal reserves (18,944 million short tonnes in 2005) [6]. Using coal in environmentally friendly and economical ways can be realized by applying more effective pollution control technologies to existing plants and by developing advanced technologies to eliminate the sources of pollution in new plants.

Research supported by the clean coal initiative has led to the enhancement of existing coal technologies to meet environmental regulations at lower costs, and at the same time has paved the way for innovative new technologies. One novel effort is the FutureGen initiative [7], a coal facility that will generate both electricity and hydrogen while sequestering the carbon emitted during the process. Cooperation from both public and private stakeholders,[2] involving the U.S. DOE, industry, national laboratories and universities will form the basis for establishing the technical and economic feasibility of the US$ 1 billion, 275 MW project. The U.S. DOE signed a cooperative agreement with the FutureGen Industrial Alliance, Inc. [8], a 10-member non-profit industrial group. A detailed review was conducted to determine potential sites for the facility, and in July 2006, four candidate sites were selected by the Alliance: Mattoon, Illinois; Tuscola, Illinois; Jewett, Texas; Odessa, Texas. These candidate sites will go through comprehensive site characterizations, including national Environmental Policy Act (NEPA) evaluations by the U.S. DOE. The engineering of the plant will be ongoing in parallel with the preparation of the plant's Environmental Impact Statement, which will be open to the public for feedback. The NEPA review is expected to be completed by the second half of 2007. At that time, the Alliance will select a final site and proceed with construction, with operation of the facility expected in 2012.

The FutureGen facility will provide benefits at several levels. As a domestic resource expected to supply the nation's energy needs for an extended period of time, coal could serve as one of the players in a diverse energy portfolio. The FutureGen project will enable effective utilization of coal by serving both transportation and stationary power sectors, while ensuring that the process is environmentally friendly and economical. Developing and demonstrating advanced technologies for the capture and storage of carbon will provide innovative solutions for managing the carbon burden of fossil resources, while enabling the continued use of an abundant and affordable domestic resource. Additionally, the demonstrated feasibility of an array of technologies (gasification, hydrogen production, car-

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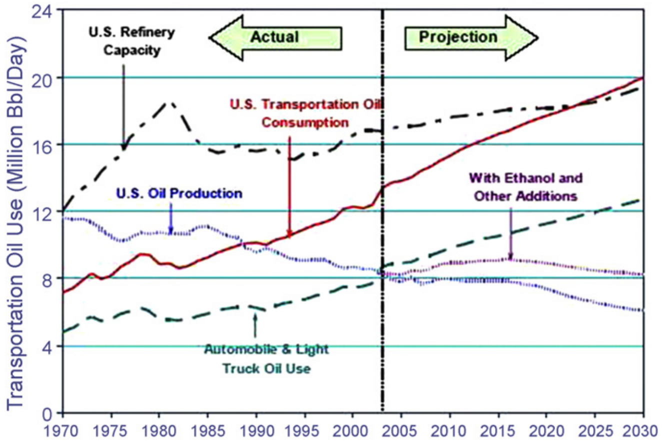
[2] The FutureGen project has expanded to also include international participants, with India and South Korea joining the efforts in April and June of 2006, respectively.



Source: Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 25.* 2006 ORNL-6974, and *ELA Annual Energy Outlook 2006, Early Release* (December 2005).

Fig. 10. Growing U.S. transportation oil gap.

bon storage in geologic formations, etc.) will be the basis of knowledge that can be shared with partners both nationally and internationally.

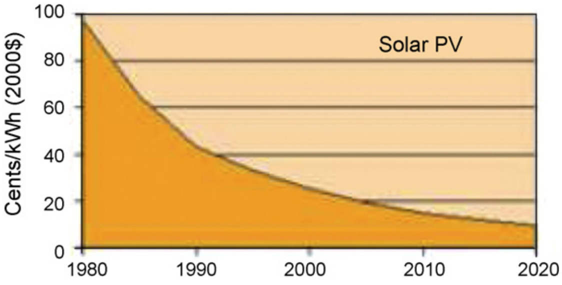
3.1.2. Nuclear energy

While nuclear power offers numerous benefits as a domestic, relatively clean and low-cost option, it also faces challenges. Nuclear facilities have higher capital expenses and there are complexities and difficulties due to necessary regulatory actions. Additionally, nuclear waste materials pose a problem in terms of storage, due to the lack of secure sites for disposal and potential misuse risks.

The Global Nuclear Energy Partnership (GNEP) is designed to enhance the collaboration of the U.S. with nations that have advanced civilian nuclear energy activities such as France, the United Kingdom, Japan and Russia [9]. The partnership will engage in activities to resolve several issues. Methods to recycle spent nuclear fuel, in combination with advanced reactor designs, will allow for the reduction of both the volume and radio-toxicity of nuclear waste materials that would otherwise need secure storage and pose environmental and security risks. The technologies that are developed may then be transferred to developing nations, providing them with secure, affordable and reliable energy. The GNEP partners will work together to ensure that these technologies are utilized for electricity generation purposes only, reducing the risks associated with exploitation of nuclear products for threatening activities.

3.1.3. Solar energy

Solar energy may be captured via photovoltaics (PV) or concentrating solar power (CSP) systems to generate electricity, or solar heating systems may be used to capture the sun's thermal energy to heat water, buildings, etc. For electricity generation, PV systems are widely used in both grid-connected and off-grid configurations. These systems make use of semiconductor materials to convert the sun's energy into electricity and are modular, allowing for their use in a wide size range, from portable devices to utility-scale applications. CSP systems utilize mirrors to concentrate solar radiation to heat a fluid, which in turn drives an electrical generator.



Source: National Renewable Energy Laboratory (NREL), Energy Analysis Office.

Fig. 11. Cost decline in solar PV systems.

3.1.3.1. Solar PV systems. The global solar PV market has demonstrated a significant growth, with worldwide PV installations reaching 1460 MW in 2005—an annual growth rate of 40% [10]. Annual global solar PV market forecasts [10] report that worldwide industry revenues will reach US$ 18.6–23.1 billion, with annual PV installations of 3.2–3.9 GW in 2010. The U.S. market share in the global PV market, however, has dropped from 12% in 2004 [11] to 7% in 2005 [10].

Japan (833 MW in 2005 [12]) and Europe (452 MW in 2005 [12]) are leading the solar PV industry in terms of capacity, followed by the U.S. (156 MW in 2005 [10]). The cumulative installed PV capacity in the U.S. is 480 MW [13]. While current PV production is silicon-based and limited by a silicon feedstock shortage, new production in the U.S. from amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium selenide (CIS) systems is expected in 2006. Costs of solar PV systems currently range from US$ 0.15 to whom it may concern: 0.25 kWh^{-1} [14],[3] compared to US$ 0.08–0.10 kWh^{-1} from conventional sources [15]. However, prices are expected to drop as technology matures and markets expand. Fig. 11 displays the price drop realized in PV systems since 1980, along with projections for further reductions.

3.1.3.2. CSP systems [16]. Currently, there are a number of CSP dish systems operating in Nevada, Arizona and Colorado and power purchase agreements have been signed for 800 MW of new CSP dish capacity in California. Trough-based CSP systems have been used to a greater extent in the U.S., with a total of 354 MW operational in California since the 1980s. A 1 MW plant became operational in Arizona. Costs of trough-based systems ranging from US$ 0.12 to 0.14 kWh^{-1} have been demonstrated commercially. Additionally, a 64 MW parabolic trough CSP system is under construction near Boulder City, Nevada.

3.1.3.3. Solar America Initiative (SAI) [17]. The Solar America Initiative (SAI) aims to reduce the cost of electricity from

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[3] Costs as low as US$ 0.11 kWh^{-1} have been realized with state incentives and net-metering rules (e.g. in California).

advanced solar technologies to US$ 0.05–0.10 kWh^{-1}, equivalent to the current cost of grid electricity. The SAI aspires to reach its cost target by 2015, but enhanced PV systems that are lower in cost will likely be delivered to the market as early as 2009–2010. Market acceptance for CSP systems is targeted for 2020. The SAI will lead to many benefits, including reduced dependence on natural gas. Additionally, solar PV systems will facilitate the formation of decentralized systems, thereby reducing the burden on the grid and risks from grid failure.

The U.S. DOE will work in partnership with industry, universities, state agencies and other organizations to achieve progress in the areas of technology development (e.g. component design, manufacturing) and technology acceptance (by addressing barriers to market introduction and expansion). The SAI demonstrates a shift in the R&D process of U.S. DOE's Solar Technologies Program from component-level research to accelerated market introduction by focusing on partnerships to eliminate manufacturing barriers and aggressively reduce cost.

3.1.4. Wind energy

Use of wind energy has grown rapidly in both the U.S. and worldwide. Global generating capacity reached 59,322 MW by the end of 2005 [18], with 9149 MW of that capacity contributed by 30 states in the U.S. [19]. The U.S. experienced a significant capacity expansion in 2005, with the addition of 2421 MW of wind capacity in that year alone. Electricity from wind currently provides electricity for 2.3 million U.S. households (approximately 0.6% of U.S. electricity generation) and the market growth rate has averaged 29% between 2000 and 2005 [20]. The U.S. wind industry's growth goal is 100,000 MW installed (or 6% of the U.S. electricity mix) by the year 2020. This is equivalent to the current contribution of hydroelectric power to the U.S. electricity mix [20].

Since 2001, the administration has supported partnerships with the industry and states to realize new wind capacity. These capacity additions have occurred mostly in rural areas, providing direct economic benefits such as increased revenues to land owners, creation of jobs and additional property tax revenues to local governments [21]. Domestically, 2000 GW of wind resources are available [22]. The U.S. DOE and industry are collaborating in developing and utilizing cutting-edge technologies to make the most efficient use of this vast resource base to overcome national energy challenges. Critical obstacles such as transmission limitations, turbine-related issues (performance, reliability, deployment) and integration with the electricity grid will be addressed via close coordination with stakeholders and targeted outreach efforts.

3.2. Transportation

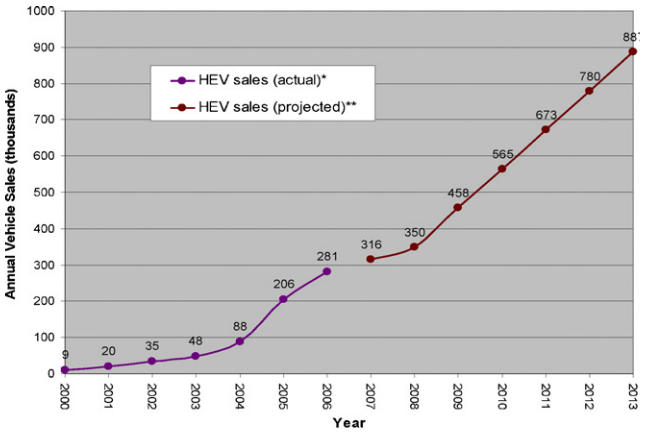
The transportation sector in the U.S. is currently highly dependent on petroleum products. Light duty vehicles (LDVs) account for approximately 60% of the transportation oil use [23]. The AEI supports three approaches that could lead to improved efficiency in transportation and to development of alternative fuels in the near-, mid- and long-term. These approaches include the development of advanced batteries, cellulosic ethanol as a fuel and hydrogen fuel cell vehicles.

3.2.1. Advanced batteries

A hybrid electric vehicle (HEV) draws on both an internal combustion engine (ICE) and an electric motor to operate the vehicle. This is accomplished by charging the electric motor with energy that would normally be lost due to activities like braking. Since the vehicle operates on electric drive for part of the time, gasoline consumption is reduced, resulting in both cost savings and environmental benefits. In the near-term, hybrids offer the potential to significantly reduce oil consumption, and do not require a major change in infrastructure. Current hybrid vehicle technology allows for 1–2 miles driving range in electric mode. Batteries for these vehicles weigh nearly 100 lb and cost approximately US$ 1600. Research is in progress to develop lithium-ion batteries with reduced weight and cost [2].

Hybrid vehicle sales in the U.S. have experienced a significant expansion, from 9500 in 2000 to 88,000 in 2004. By the end of 2005, the number of HEVs on the road grew to over 212,000 [24]. For actual and projected U.S. HEV sales see Fig. 12. The Energy Information Administration (EIA) predicts that HEVs will increase from 0.5% of new LDV sales in 2004 to 9% in 2030 [5]. If one million (0.8%) of the vehicles on the road today, which on average get 22.4 miles to the gallon, are replaced with vehicles that get 80 miles to the gallon, a potential savings of approximately 400 million gallons of gasoline (or about 9.5 million barrels) could be realized annually [25].

Another form of hybrid vehicle technology is the plug-in hybrid electric vehicle (PHEV). These vehicles are similar to traditional HEVs in that they use both gasoline and electricity to drive the vehicle, but also differ in that they can be *plugged-in* to an electrical outlet to charge the batteries. The charging process could make use of the off-peak electricity production of utilities. PHEVs have the potential to extend the electric driving range of traditional HEVs and the fuel economy, if advanced batteries are developed [2], and could significantly reduce oil use [26]. However, plug-ins are still in the demonstration phase and face several challenges. Batteries used in PHEVs will need



Source: Data through 2006 are from http://www.hybridcars.com and data beyond 2006 are from JD Power and Associates,HEV Outlook.

Fig. 12. Past and projected annual hybrid electric vehicle sales in the U.S.

eight to ten times the energy storage capacity of conventional HEV batteries and achieving a 15-year life for these batteries is a challenge. Furthermore, issues concerning cost, as well as cycle life and performance of PHEV batteries still need to be resolved. Advancements in HEVs and PHEVs will also serve as a building block for longer-term technologies like hydrogen fuel cell vehicles.

3.2.2. *Cellulosic ethanol*

Ethanol production in the U.S. reached close to 4 billion gallons in 2005—this represents an increase of over 120% since 2001 [27]. According to the National Ethanol Vehicle Coalition, there are currently 1000 ethanol fueling stations in the U.S. The 1000th station recently opened in Bemidji, Minnesota and marks the 600th station opening for 2006 [28].

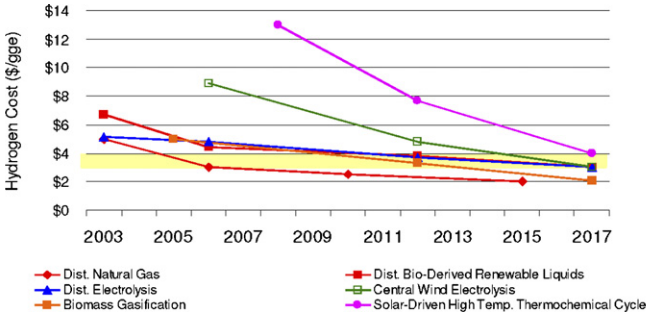
Process steps in ethanol production involve fermentation and distillation to create an alcohol-based fuel. Traditionally, starch-based crops such as corn, barley or wheat are converted via this process. Ethanol may be blended with gasoline in differing percentages, the most common being 85% ethanol to 15% gasoline (called E85). This blend is used in flexible fuel vehicles (FFVs). Currently, there are over five million FFVs on the road [29]. GM is producing 400,000 FFVs in 2006 [30], and Ford is producing 250,000 FFVs [31]. If the percentage of ethanol is higher such as 95%, the fuel is considered an alternative fuel according to the Energy Policy Act (EPACT) of 1992 [32]. Lower blends (10% ethanol) are also available—these fuels are not defined as alternative fuels under EPACT but they improve the quality of gasoline and reduce emissions.

Currently, research efforts are focused on cellulosic biomass to produce ethanol, including wastes from agricultural activities (e.g. corn stover, sugarcane bagasse) or from industrial practices (e.g. paper pulp) and specific energy crops harvested for fuel (e.g. switchgrass). Cellulosic ethanol technology will enable use of a more diverse resource base, allowing for production nationwide from locally available resources.

The minimum ethanol sales price of US$ 2.26 gal^{-1} in 2005 was reduced from US$ 5.66 in 2001 [33].[4] The target for competitive cellulosic ethanol in 2012 is US$ 1.07 gal^{-1} [34]. The AEI seeks breakthrough technologies to make cellulosic ethanol cost competitive with corn-based ethanol by 2012. This could enable 30% of the Nation's current fuel use to be supplied by ethanol by 2030 [2].

3.2.3. *Hydrogen fuel cell vehicles*

Hydrogen is an *energy carrier*, as opposed to an *energy source*. Therefore, it needs to be generated from another resource—this poses challenges and complexities, but at the same time, it offers an opportunity to utilize a diverse set of domestic resources, reduce dependence on foreign oil, reduce greenhouse gas emissions and provide for a sustainable energy system. Renewable resources, fossil resources in conjunction with carbon sequestration, or nuclear energy may be utilized for generating hydrogen. At the same time, fuel cell vehicles provide greater than double the fuel economy of gasoline ICE vehicles and 50% greater fuel economy than HEVs [35].



Source: U.S. Department of Energy (DOE), Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program.

Fig. 13. Distributed hydrogen production (near term approaches)—status vs. goal.

Currently, the U.S. produces about nine million tons of hydrogen per year [36], and approximately 700 miles of hydrogen pipelines (compared to over one million miles of natural gas pipelines) safely deliver hydrogen to industry [37]. If hydrogen technology achieves its full market potential, over 11 million barrels of oil per day could be displaced and the emissions of more than 500 million metric tonnes of carbon could be prevented [38].

To realize the full potential of hydrogen, there are several key challenges related to both the technology and economic/institutional factors. Critical path technologies[5] rely on achieving targets related to hydrogen storage, fuel cell cost and durability, and hydrogen cost: over 300 miles range for storage; US$ 30 kW^{-1} fuel cell system cost; 5000 h fuel cell durability; US$ 2–3 gge^{-1} hydrogen cost (see Fig. 13 for the status of near-term hydrogen production approaches) [39].

The department has partnered with automotive and energy companies (FreedomCAR & Fuel Partnership) to address critical issues in the development of hydrogen technologies. Significant progress has been realized through the Partnership activities. Key achievements include [40]:

- Reduction in the high-volume fuel cell system cost to US$ 110 kW^{-1} (Fig. 14).[6]
- Reduction of the cost of hydrogen from natural gas to US$ 3 gge^{-1}.[7]
- Achievement of 2000 h fuel cell durability (Fig. 15).
- Validation of integrated technologies through demonstration of over 60 fuel cell vehicles and 10 hydrogen fueling stations.

In parallel with the development of technologies, the following challenges need to be addressed:

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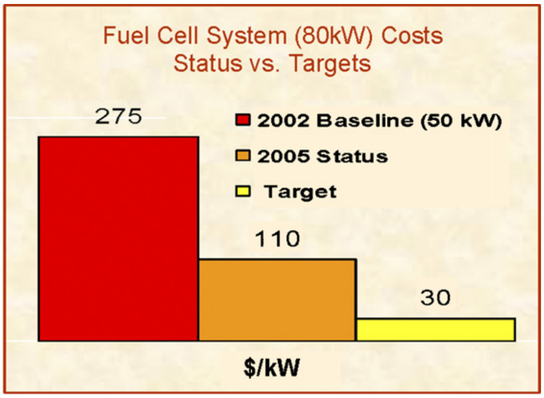
[4] Assumptions: US$ 53 tonnes^{-1} feedstock and 10% return on investment.

[5] The main focus of the U.S. DOE Hydrogen Program's research is transportation fuel cells. However, stationary and portable fuel cells are supported as well.

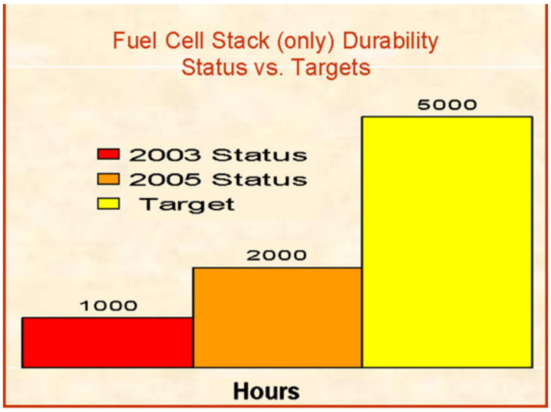
[6] The U.S. DOE Hydrogen Program's target for 2015 is US$ 30 kW^{-1} [39].

[7] The U.S. DOE Hydrogen Program's target is US$ 2–3 gge^{-1}; delivered, untaxed, at the pump and independent of the technology pathway [39]. Also note that 1 kg of hydrogen contains nearly the same energy as a gallon of gasoline.



Source: U.S. Department of Energy (DOE), Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program.

Fig. 14. Fuel cell system (80 kW) costs—status vs. targets.



Source: U.S. Department of Energy (DOE), Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program.

Fig. 15. Fuel cell stack (only) durability—status vs. targets.

- Development of appropriate codes and standards, taking into account safety and global competitiveness issues.
- Investment needs of the hydrogen delivery infrastructure.
- Education of stakeholders (safety and code officials; local and state governments; students; communities).

4. Well-to-wheels analysis for transportation

Transportation energy use poses a major concern in terms of its dependence on oil, its impact on the air quality of the nation and its contribution to global warming. The development of alternative fuels and advanced vehicle technologies, while providing opportunities for solutions, also provide a variety of options that require detailed analyses to aid decision makers. When evaluating different vehicle technologies and fuels, environmental and energy trade-offs need to be considered along with cost projections. Cost analyses also help to identify where R&D dollars should be focused. The entire cycle of operations, from harvesting the feedstock and producing the fuel, to delivering that fuel to the vehicles and the operation/disposal of vehicles, must be taken into account for a comprehensive and accurate evaluation.

4.1. Analysis tools

Models have been developed to provide structure, transparency and enhanced understanding of both fuels and vehicle technologies from a “well-to-wheels” perspective. The hydrogen analysis (H2A) [41] and Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) [42] models serve as valuable tools in examining a diverse array of fuel/vehicle pathways and their implications. The pathways that have been evaluated by these models may be categorized into three groups based on the fuel used: gasoline, ethanol and hydrogen-based vehicles. Vehicles using gasoline may either be internal combustion engine (ICE) vehicles operating fully on gasoline, or hybrid electric vehicles (HEVs) operating on both gasoline and electricity. For ethanol vehicles, use of “E85” is considered; however, the feedstock for that ethanol may differ. Currently, nearly all of the ethanol produced domestically is derived from corn. Advanced technologies for generating ethanol involve the use of cellulose-based biomass material such as residues from forestry and agricultural activities, municipal solid wastes and energy crops.

Hydrogen fuel cell vehicles considered in the analyses involve a diverse set of pathways arising from the variety of feedstocks and methods to produce hydrogen. Each pathway is considered for different timeframes (2005, 2015 and 2030), to reflect technology advancements and cost reductions that will occur with time. In the current stage, distributed production of hydrogen via natural gas reforming and wind electrolysis, as well as central, larger-scale production of hydrogen via wind electrolysis and gasification of biomass or coal (with carbon sequestration) are considered.[8] Distributed production of hydrogen from wind and natural gas are also considered for 2015, with improvements in technology anticipated. Cases farther in the future (2030) foresee additional progress in technologies and consist of centralized production of hydrogen based on wind electrolysis, gasification of biomass or coal (with carbon sequestration) and the nuclear sulfur-iodine process.

4.1.1. The H2A model

Analysis of hydrogen systems involves many complexities and requires various assumptions. Prior to 2003, even though valuable analyses were conducted, results from these analyses were inconsistent. The H2A model effort was initiated in 2003 to overcome these discrepancies and to draw on the knowledge base of analysts, creating an understanding of the differences and providing a transparent, consistent and standard methodology that can be validated by industry. Any modeling effort is based significantly on the assumptions used in calculating values. Therefore, confirmation of how closely the model values and assumptions reflect real-world industry conditions is key to the validity of a model.

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[8] The current stage represents technologies of 2005, which are in the laboratory and have not been validated at full scale.

Analysts developing the H2A model interact closely with members of industry[9] to continuously seek guidance on the accuracy of H2A assumptions[10] and recent technology developments.

H2A is a spreadsheet-based model, looking at the life-cycle costs of hydrogen production and delivery on a well-to-gate basis for central-plant technologies and a well-to-pump basis for forecourt technologies. Technologies considered for assessment are those having commercialization potential and an adequate amount of information available to enable calculations. They are categorized as current technologies (2005), advanced technologies (2010–2020) and longer-term technologies (2020–2030). The hydrogen production processes are characterized as forecourt (smaller distributed facilities located on-site at refueling stations, sized at 100 and 1500 kg H_2 per day) and central (large plants, sized at larger than 50,000 kg H_2 per day). The forecourt hydrogen production techniques include natural gas steam methane reforming and electrolysis (utilizing the grid electricity mix). Reforming of ethanol and methanol on the forecourt scale are two additional methods currently undergoing evaluation, with results to be made available in the future. The central hydrogen production methods include:

- Coal gasification (with and without electricity co-production; with and without carbon sequestration).
- Natural gas steam methane reforming (with and without carbon sequestration).
- Biomass gasification.
- Nuclear processes (high-temperature sulfur iodine thermochemical, high-temperature steam electrolysis and standard electrolysis).
- Wind-electrolysis (with and without electricity co-production).

Hydrogen production technologies need to be considered in conjunction with delivery pathways and related infrastructure components. Therefore, hydrogen delivery analysis in H2A considers various delivery pathways (gaseous hydrogen via pipelines or truck tube trailers and liquid hydrogen via cryogenic trucks), related components (pipelines, compressors, liquefiers, etc.) and scenarios (cases specific to a geographic region).

Analysis of hydrogen production and delivery technologies involves a comprehensive assessment of system component costs (capital, operation and maintenance, etc.), as well as an assessment of the feedstock and energy consumption and emissions of greenhouse gases (GHGs) and other pollutants. The discounted cash flow methodology is built into the standardized spreadsheets of the model, yielding the cost contributions of each component in US$ per kg H_2, efficiency of the system, feedstock and fuel consumption, and emissions. Additionally, sensitivity and uncertainty analyses are conducted to better understand feedstocks and components most susceptible to changes in assumptions and the areas most affected by uncertainties.

In addition to cost, an essential pathway analysis is the life-cycle impact on the total energy use, the fossil fuel use, the petroleum use and the greenhouse gas emissions. In the life-cycle approach, which includes key output information from the H2A production and delivery models for the hydrogen pathways, the energy and environmental implications of different technologies are established by employing data from another comprehensive model, the GREET model, explained in more detail in Section 4.1.2.

4.1.2. The GREET model

The GREET model is a multi-dimensional spreadsheet-based model developed by Argonne National Laboratory (ANL) and sponsored by the DOE Office of Energy Efficiency and Renewable Energy (EERE). This model focuses on the energy and emissions implications of the full cycle of transportation technologies, including the fuel cycle (from the source to its use in vehicles) and the vehicle cycle (from the production of materials to assemble a vehicle to the eventual disposal and recycling of these vehicles). GREET evaluates different vehicle/fuel combinations to delineate the energy and environmental consequences of the system, looking at:

- Total energy consumption.
- Fossil fuel consumption (petroleum, natural gas and coal).
- Petroleum consumption.
- Emissions of carbon dioxide and carbon dioxide-equivalent gases (methane and nitrous oxide).
- Emissions of criteria air pollutants (volatile organic compounds, carbon monoxide, nitrogen oxides, particulate matter with sizes smaller than 10 μm and sulfur oxides).

The comprehensive set of fuel pathways and vehicle technologies that the model investigates are evaluated over near- and long-term time periods, to take into account improvements in the performance of environmental and energy values due to the development of technologies. The following vehicle technologies are evaluated, along with 30 fuel-cycle pathways:

- Spark ignition engines (conventional and direct injection).
- Compression ignition engines (direct injection).
- Hybrid electric vehicles (grid connected and grid independent).
- Electric vehicles (battery powered).
- Hydrogen fuel cell vehicles.

4.1.3. Analysis results

The well-to-wheels analyses conducted for transportation applications [43] have resulted in a detailed understanding of different fuel/vehicle options and their relative impacts on petroleum use and GHG emissions. Fig. 16 displays these findings. Overall, the use of fuel cell vehicles in conjunction with

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[9] Industry participants involved in validating the H2A model include: AEP, BOC, BP, Chevron, Eastman Chemical, Entergy, ExxonMobil, Ferco, Framatome, General Electric, Praxair, Stuart Energy and Thermochem.

[10] For a detailed listing of H2A assumptions, see http://www.hydrogen.energy.gov/h2a_prod_rules.html.

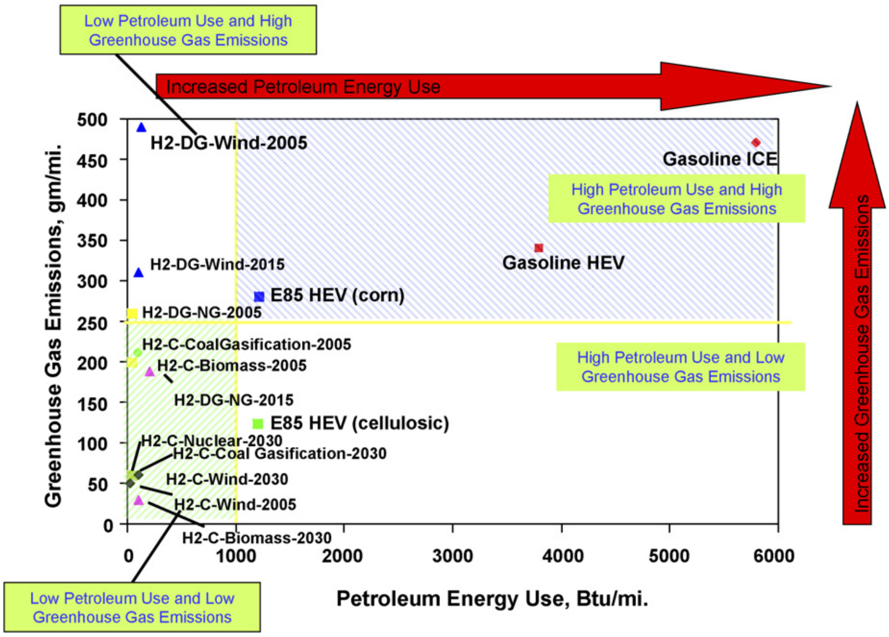

Fig. 16. Well-to-wheels analysis results for transportation fuel options.

hydrogen produced from a variety of pathways (except a couple exceptions) resulted in lower petroleum use and GHG emissions. Gasoline HEVs demonstrated improved outcomes in terms of both petroleum use and GHG emissions, while ethanol-based HEVs yielded even further benefits. For ethanol HEVs, corn-based and cellulosic ethanol were about equivalent in terms of petroleum use, but cellulosic ethanol provided significant reductions in terms GHG emissions.

The lowest petroleum use and GHG emissions are achieved by hydrogen fuel cell vehicles involving the following pathways:

- Central hydrogen production from coal, with carbon sequestration, in 2005 and 2030.
- Central hydrogen production from biomass, in 2005 and 2030.
- Central hydrogen production from wind, in 2005 and 2030.
- Central hydrogen production from nuclear energy in 2030.
- Distributed hydrogen production from reforming of natural gas in 2015.

Fuel cell vehicles powered by hydrogen produced in a distributed manner with wind energy (utilizing technologies in 2005) use minimal petroleum, but emit more GHGs than gasoline ICE vehicles. Even though wind is a renewable resource and the use of hydrogen in fuel cell vehicles does not result in GHGs, the excessive quantity of GHG emissions seen here are due to the use of fossil resources for back-up power generation (to balance out irregularities with the wind resource) to maintain the production capacity at ∼100%.

When the technologies of 2030 are used to produce hydrogen from biomass resources in a distributed approach, and the generated hydrogen is used in fuel cell vehicles, the resulting petroleum use and GHG emissions are the lowest, in comparison to the other fuel/vehicle alternatives investigated.

5. Conclusions

The supply and demand for energy in the U.S. has changed over the last century. The increased dependence on fossil resources, especially in the transportation sector, has created several challenges. The reliance on imported oil in the transportation sector has led to geo-political complexities, as well as concerns regarding climate change. The health impact of air emissions from both the transportation and stationary power sectors has also become a growing concern. As demand for energy increases and consumption proceeds at a rapid rate, innovative solutions to utilizing alternative sources of energy are needed, in conjunction with the more efficient use of fossil resources.

The Advanced Energy Initiative addresses these challenges by providing resources for research and development of clean energy technologies, and by channeling the talent and innovation of the nation's scientists and engineers toward that goal. Since the Hydrogen Fuel Initiative was launched in 2004, DOE has awarded over US$ 625 million (over US$ 800 million with private cost share) for research and development of hydrogen and fuel cell technologies. In addition, the AEI provides support for development of hybrid-electric technologies, biofuels, clean coal technologies, and solar and nuclear energy. These research and development programs are supported by comprehensive life-cycle analysis efforts, using models such as H2A and GREET, that will enable a better understanding of the characteristics and trade-offs associated with advanced energy options, and informed decisions and solutions for our Nation's energy challenges.

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