With petroleum production on the cusp of decline, the world must find a new fuel to power its transportation system. What role will hydrogen technologies play in that transition?

It is hard to imagine a world without oil. Beginning with the flight of the Wright brothers in 1903 and the production of the Ford Model T in 1908, petroleum came to influence almost every aspect of life, from transportation to agriculture, construction, and household products. And from an engineer's point of view, petroleum is a marvel: it has a very high energy density and is relatively easy to collect, transport, and store. Even today, more than 30 years after the oil shocks of the 1970s, the world economy is dependent on oil in a way that no other energy source can claim.

But the reign of oil is coming to an end. For a variety of reasons—geological, economic, political, and ecological—the rate of petroleum production will likely remain flat or even fall in
The coming decades. The International Energy Agency last year published a report that predicted that crude oil production will increase by less than 5 million barrels a day over the next 20 years, and that increase will be due entirely to projected production from currently undiscovered fields. Other oil industry experts believe that even this modest increase is unachievable.

This decline in petroleum availability has awakened many people to the unsustainability of our current level of petroleum use. An increase in conservation and efficiency is necessary in how we use the petroleum that is produced. Already, widespread global initiatives have taken place in light of this realization, from the movement to replace disposable plastic bottles and bags with reusable containers, to the development of fuel efficient hybrid electric vehicles. There is a push to develop alternative fuels to alleviate dependence on a single fuel source for transportation while simultaneously reducing harmful environmental effects from CO2 emissions. Even now, some alternatives to petroleum are used in transportation.

Perhaps the most widely anticipated alternative fuel is hydrogen, which has been the subject of research for decades. Hydrogen has some very attractive properties: it has the highest energy density by mass of any potential fuel and it burns cleanly, creating only water vapor during efficient combustion. Some pundits have talked optimistically about the development of a so-called hydrogen economy, where hydrogen takes on the central role in our society that petroleum has played for the past 100 years.

As we leave behind the Abundant Petroleum Era (see sidebar on page 35) and begin a transition—into first an Energy Awakening Era, in which we become acutely aware of the consequences of our energy use, then into the Energy Evolution Era, where the energy market is diversified, leading into a New Energy Era, based on alternative energy sources—it will be important for government and industry to neither hinder nor overdevelop any one option. All the energy cards need to be laid out on the table, so that the best option will evolve under the forces of the marketplace, future energy needs, and socioeconomic issues related to energy supply.

To this end, it will be crucial to find out whether hydrogen can live up to its great promise. Is a hydrogen economy actually feasible? And is it the most practical means to power society?

The key component of a hydrogen-powered transportation sector will be the proton exchange membrane fuel cell. PEM fuel cells use hydrogen and oxygen to generate electricity, with water and heat as byproducts of the electro-chemical reaction. They have been recognized as the fuel cell technology of choice for transportation because of their high power density, high efficiency, rapid startup capability, clean operation, and flexibility in terms of the source of hydrogen fuel.

With a huge joint effort made by various automotive manufacturers such as General Motors and Honda. In 2008, GM's Project Driveway implemented the first large-scale market test of fuel cell vehicles, which took place throughout New York City, Washington, D.C., and Southern California. Honda made its Clarity fuel cell car available for lease in Southern California in the summer of 2008. It is expected that such vehicles will be on the market in limited quantities in the near future.

Several hurdles still stand in the way of full implementation, and additional research efforts are needed. To compete favorably with internal combustion engines and hybrid cars, PEM fuel cells need to address a number of issues, including performance, durability, and cost. Additional performance gains are expected as a result of the U.S. Department of Energy's research emphasis in the areas of electrocatalysts, low- and high-temperature membranes, diffusion media, and bipolar plate material.

The cost of fuel cell stacks is primarily governed by the catalyst, membrane, and bipolar plates. In spite of a longstanding target of $40 per kilowatt for automotive fuel cells, a recent survey of fuel cell manufacturing conducted by the U.S. DOE revealed that the low-volume costs for fuel cells are still in excess of $1,800 per kilowatt. Of course, as the technology continues to advance, production costs will be driven down due to reduction of catalyst loading and economies of scale.

Water management is considered one of the largest outstanding issues of PEM fuel cells, due to complications of water accumulation inside the cell and subsequent freezing following shutdown in cold climate conditions. This can hinder the startup of fuel cell vehicles.
An experimental set-up at the PEM fuel cell research facility at the Rochester Institute of Technology uses a high-speed camera to observe water formation in the channels of an operational fuel cell. Water droplets can be clearly seen in the image at left.

because of ice blocking reactant gas flow.

Large research initiatives in this area are currently under way in academia and industry. One of the primary goals of this research is to gain a better understanding of water transport dynamics within fuel cells, and to ultimately develop methods of mitigating startup concerns due to water production and accumulation. Visualization is one technique used to study liquid water within a fuel cell. Rochester Institute of Technology in New York, for instance, uses transparent fuel cells with high-speed imaging to study water production and transport within the cell.

As a major partner in a U.S. DOE sponsored research grant with RIT and Michigan Technological University, General Motors Fuel Cell Research Laboratory in Honeoye Falls, N.Y., is engaged in conducting studies on liquid water within a PEM fuel cell. To accomplish this, GM utilizes neutron radiography, a technique that uses a neutron beam that passes through an operating fuel cell. The attenuation of the beam reveals the 2-D measurement of water thickness.

If cost and performance issues can be resolved, then PEM fuel cells will likely be a core component of a hydrogen economy. These fuel cells are ideally suited to transportation purposes, because of their high efficiency and a refueling time comparable to petroleum fuels. As with electric vehicles, PEM fuel cells will reduce air pollution and CO₂ emissions.

Some skeptics claim that creating the necessary infrastructure to support a hydrogen-fueled transportation system will be too costly to be practical. Yet hydrogen can be produced from a variety of sources including natural gas reforming, biomass, and water splitting. U.S. Department of Energy figures show that in 2008, 95 percent of hydrogen produced in the U.S. came from natural gas feedstock.

Hydrogen from natural gas could provide a firm stepping stone as the energy system evolves away from petroleum. The natural gas infrastructure that was built during the Abundant Petroleum Era can be utilized to construct a major component in the hydrogen infrastructure. On-site hydrogen generation using the natural gas infrastructure eliminates the challenge of efficiently transporting a low energy-to-volume ratio fuel.

Natural gas reforming is not considered to be a long-term option since carbon dioxide is produced in the process. However, when the reformed hydrogen is used in fuel cell vehicles, these greenhouse gas emissions are still considerably less compared to those produced by an internal combustion engine vehicle. Another process, biomass conversion, typically requires high temperature, but through advances in genetic engineering special microorganisms could be developed to commercially produce hydrogen by decomposing organic waste material. Such conversion would be carbon-neutral.

Electrolysis and artificial photosynthesis can generate hydrogen by splitting water molecules. Electrolysis can be driven by a variety of energy sources, such as the electrical grid or renewable sources including solar and wind, for on-site or distributed hydrogen generation. Artificial photosynthesis splits water with sunlight to create hydrogen in a process analogous to photochemical reactions in plants. Advancement towards this ideal energy conversion process has shown great promise utilizing an earth-abundant non-noble catalyst in neutral water
at atmospheric temperature and pressure, as reported by Massachusetts Institute of Technology in the journal Science in 2008 (Vol. 321, pp. 1072-1075).

Once oil production reaches its upper limit, conservation and a reduced dependence on petroleum will become core societal values. In addition, the long-term environmental effects of the Abundant Petroleum Era will continue to emerge, and mitigation and future prevention of that damage will remain dominant priorities.

Fortunately, the initial investments into petroleum alternatives for transportation, such as PEM fuel cells, will start to pay off, and the energy market will become diversified with potentially viable solutions. These new alternatives will contrast petroleum’s greatly fluctuating prices and unknown supplies with stability in the energy market. The initial investments will see rapid growth as the new alternatives outpace petroleum as the New Energy Era approaches.

During the second half of this century, petroleum use will be limited. Non-fuel components such as lubricants, waxes, asphalt and road oil, and petrochemical feedstock for chemicals, plastics, and medicine will remain. And remote operations such as arctic research and deep forest explorations will be difficult to support using sustainable options; hydrogen would be too costly to transport and conditions may be too cold for biodiesel or batteries. Such applications may demand the continued use of petroleum-based fuels.

Electrical generation using petroleum will most likely have been completely phased out by then as well, due to the large fuel costs to operate these power plants. Petroleum’s cost and availability will limit it to small-scale use with cheaper sustainable options becoming dominant.

The New Energy Era represents more than just alternative energy solutions. Engineers and consumers will have to embrace new ways of thinking about energy consumption on the global scale. Energy will no longer be cheap and expendable, and its use will not be viewed as inconsequential. As a result, conservation will be of primary concern. People will have to shift their thinking towards more sustainable lifestyles, with energy self-contained buildings and energy efficient products.

Energy usage considerations will even extend to waste and garbage production, where ways to reduce and reuse waste in a more sustainable manner will be common practice. Efficiency gains will be taken at every opportunity with new designs and replacement of old, inefficient equipment. Waste thermal energy recovery will be considered for all new equipment to dramatically boost overall efficiencies.

In addition, it is probable that no single technology or fuel will dominate in the future the way that the internal combustion engine and petroleum have previously ruled. Rather, geographically specific solutions are more likely to emerge in response to local market conditions. Areas with ample water supplies, such as the Northeastern U.S., could allow for hydrogen production from electrolysis without burdening municipal water systems. This would enable fuel cell vehicles to operate with zero emissions provided the electricity for the electrolysis came from a sustainable source. Areas such as the U.S. Southwest, could be too hot for current membrane technology, requiring very large radiators in the vehicles. Alternatively, these areas do typically have large quantities of sunlight which would allow for clean operation of electric vehicles that are charged with photovoltaics. Urban areas with high population densities could use hydrogen produced from conversion of biomass in plentiful organic wastes.

At present, the looming crisis caused by the decline in petroleum production and the need to control greenhouse gas emissions exemplifies the need for new energy solutions. These technological solutions must also be accompanied by a change in mindset. It will be necessary to rethink how we live our everyday lives and adapt in order to preserve the quality of life that we are accustomed to. These changes in utilization patterns and lifestyle will help to secure a sustainable future. The conservation practices that are developed as we progress through this century’s energy eras will be firm examples for generations to come, who will apply this fundamental philosophy to food, water, and other life-sustaining resources.

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**the energy roadmap**

Energy use touches aspects of everyday life. The prospect of reduced access to petroleum means that the world as we have known it for the past century is going to begin a radical transition. This transition will unfold over four successive eras, each distinctly defined by the perceived extent of petroleum reserves, the supply and demand situations, and the national political and international geopolitical scenarios that are in play.

/// The Abundant Petroleum Era [1900 to present]: A time of extensive use of petroleum to support our transportation needs without much consideration given to the consequences of complete dependence on one resource or its environmental impacts.

/// The Energy Awakening Era [Present to 2035]: A period when scarcity and environmental effects of petroleum have motivated the pursuit of alternative fuels to replace petroleum and mitigate human influence on the climate.

/// The Energy Evolution Era [2035 to 2080]: This period will see declining petroleum use in the transportation sector as a result of a continually evolving and diversified fuel market. Some alternatives will be weeded out during this time.

/// The New Energy Era (2080 and beyond): By this point, a clear path forward will have emerged. We will have found a means to meet the world’s energy demand in a way that recognizes and incorporates environmental concerns. This roadmap of future energy developments provides a framework for our approach toward sustainable energy solutions.