The Economics of Energy Options

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Abstract

Increasing demand for energy, diminishing stocks of oil and natural gas, and the public's desire to enhance environmental quality, particularly by reducing greenhouse gas emissions, all point to the need for improved materials. For example, generating electricity from the most abundant fossil fuel, coal, efficiently and with no environmental damage, presents notable challenges to develop higher performance materials. Technologies exist to transform one fossil fuel to other uses, such as coal to a gas or liquid. New materials that increase the efficiency of the transformation and lower its cost would provide valuable flexibility. Materials should be evaluated in terms of their entire lifecycle in order to discern which will make the greatest contribution. Because society has many pressing needs, both commercial value and contribution to fundamental materials science should guide priorities in materials research.

Introduction

The energy sector offers many challenges and opportunities for materials science, which can be placed in context by examining the total amount of energy used now and total energy use projected to 2030, the distribution across nations, and the issue of carbon dioxide emissions. The developed nations use 15 times as much energy per capita as the developing nations. Energy efficiency has improved over time, with vast potential for further improvement. For good materials science to become commercially successful, the properties and cost of materials must compete with other technologies. One important example is developing lighter materials for the frame, body, and drive train of an automobile. Lowering vehicle weight is critical to improving fuel economy, but the lighter materials must satisfy stringent safety, durability, manufacturing, and cost criteria.

Producing electricity with no carbon dioxide emissions is a major frontier for materials research. Technologies for capturing carbon; piping and storing hydrogen; making a new generation of safer, more efficient nuclear reactors; producing electricity from sunlight, wind, and other renewables; and finding better ways of storing electricity pose major challenges and offer huge rewards. Improving the usefulness of these technologies requires an understanding of the markets for energy and the tools that use energy, as well as the level of success that must be achieved for an invention to be interesting commercially.

A brief overview of the current world energy situation can place into context some of the challenges that it poses to materials scientists and engineers and identify some benchmarks in terms of performance and cost that advances in materials science must achieve to become commercially appealing.

The World Energy Situation

Developed nations use huge amounts of energy. For example, in 2005, the industrialized nations used about 240 quadrillion British thermal units (quadrillion BTUs, or quads; i.e., 250 exajoules, EJ), whereas developing nations used about 207 quads (220 EJ), for a total of 447 quads (470 EJ).

If all of this energy came from coal, the world would use 22 billion tons each year. On a lifecycle basis, Hendrickson et al.[1] showed that extracting, transporting, and burning coal puts more pollutants into the environment and results in more injuries and deaths than using oil, natural gas, or nuclear technology. They also showed that, on a lifecycle basis, improved materials can have major effects on resource and energy use, from reducing the weight of vehicles to selecting materials for roads and bridges. Advanced materials, such as lighter metals and composites, generally require more energy for manufacture than do traditional materials. In addition, composites cannot be readily recycled. Thus, a lifecycle analysis is needed to determine whether the use of any new or traditional material will make a positive or negative contribution to environmental quality and sustainability.

Although Earth contains large amounts of fossil fuels, they are not generally in the most desirable form. For example, the best combined cycle gas turbine can produce electricity about 50% more efficiently than the best pulverized-coal–steam turbine. Similarly, aircraft and cars burn liquid fuels; they cannot be easily modified to use coal. However, advanced materials make possible the conversion of coal to liquids, increasing the value of the large coal reserves in the United States.

As **Figure 1** shows, economic activity—gross domestic product (GDP)—has grown about twice as fast as energy use, although electricity use has grown at roughly the same rate as the GDP. Energy use and population have been growing at the same rate, but more slowly than GDP, indicating that the world, on average, is getting richer, although the greater overall income is far from evenly distributed. In 1970, energy expenditures were about 8% of GDP. The increase in oil prices (and other fossil fuel prices) by the Organization of the Petroleum Exporting Countries (OPEC) pushed energy expenditures to 13.7% of GDP in 1981. Since then, energy expenditures fell sharply to 7.4% of GDP, but they have been rising again as oil prices have increased.

Table I provides a detailed picture of energy consumption by region and fuel from 1990 to 2004 with projections to 2030. I caution that energy projections are notoriously inaccurate, particularly because they assume that peak oil production will

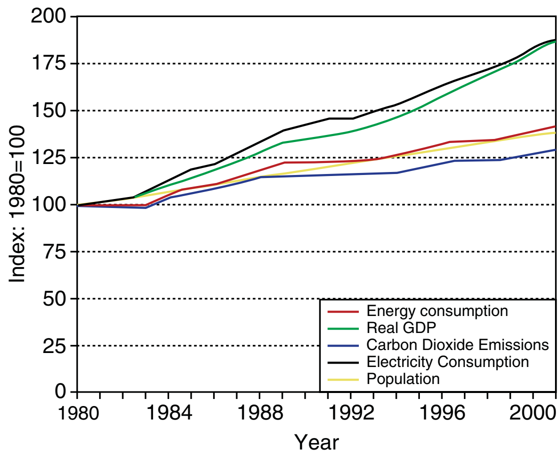

Figure 1. World trends in energy consumption, carbon dioxide emissions, and population growth through 2001.[2]

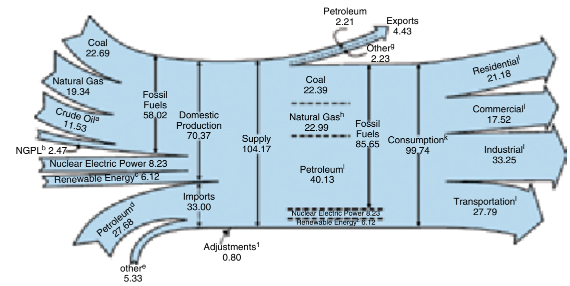

Figure 2. United States energy supply and use in 2004.[4] NGPL is natural gas plant liquids.

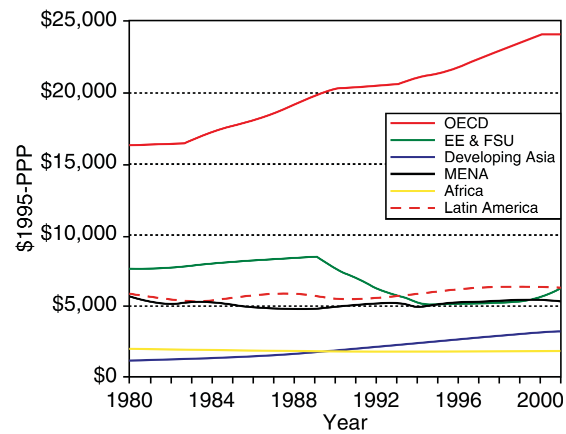

Figure 3. Gross domestic product (GDP) per capita for geographical regions worldwide.[5] *Note:* EE & FSU, Eastern Europe and the former Soviet Union; MENA, Middle East–North Africa; OECD, Organisation for Economic Cooperation and Development; and PPP, purchasing power parity.

not occur until after 2030 and that carbon dioxide emissions constraints will not be stringent during this period.

North America is projected to use 50% more energy in 2030 than in 2005 with the rest of the Organisation for Economic Cooperation and Development (OECD) nations increasing their consumption only slightly. Oil, natural gas, and coal make up the majority of increased use, whereas natural gas is the largest supplier of additional energy for the rest of the developed nations. Non-OECD Asian nations are projected to increase energy use more than 2.2 times, and the growth of energy use in other developing nations is expected to be somewhat less rapid. To achieve this growth in energy use, the supply of all fuels is projected to increase rapidly. Fossil fuels (oil, natural gas, and coal) produce 86% of world energy today and are estimated to produce the same proportion in 2030.

Figure 2 shows the sources and uses of energy for the United States in 2004. The total supply of energy was 104.2 quads (including 33 quads of imported energy) of which 4.4 quads were exported and 99.7 consumed. Eighty-six percent of the energy came from fossil fuels. Of the total energy, the residential sector used 21%, the commercial sector used 18%, the industrial sector used 33%, and the transportation sector used 28%.

Energy use not only provides comfortable temperatures in our homes and workplaces, it also relieves many people of the hard physical labor that burdened people for most of human history and provides us with communication, computing, transportation, and entertainment. The average U.S. resident uses 350 gigajoules (GJ) of energy per year, which is equivalent to having 45 horses or 450 workers per working hour. In the sense of having command over so much energy, the average U.S. resident is among the richest and most powerful people ever to have lived. In contrast, the poorest people in the world use no fossil fuels, extracting energy only from burning biomass or dung.

Figure 3 shows economic activity (GDP) per capita, a rough indicator of income per capita by region. The most startling aspect of the figure is the high and growing incomes of the OECD nations. The incomes of Eastern Europe and the former Soviet Union dropped rapidly after the breakup of the latter, and now are increasing. The incomes of developing Asian countries are increasing rapidly, but there is income stagnation in the rest of the world. The extremely low income level in Africa is not rising; and the incomes in the Middle East and North Africa (MENA) are also not rising. There is only the hint of an increase in Latin America.

Figure 4 shows carbon dioxide emissions per capita. The G-7 nations (Canada, France, Germany, Italy, Japan, United Kingdom, and United States) and OECD nations emit roughly three times the world average. Eastern Europe and the former Soviet Union are also high emitters, even though per capita income is much lower than in the OECD nations; they use energy inefficiently. The non-OECD nations emit little CO_2 per capita, as they are so poor that they use little fossil fuels. Developing Asia has increased emissions over this period, whereas African emissions are flat and are at the bottom.

Energy Efficiency

The United States economy used much more energy during the period of major infrastructure investment. A measure of the efficiency of energy use can be obtained by scaling energy use per dollar of GDP (with the year 1900 equal to 100). Specifically, energy use per dollar of GDP rose from 60 in 1880 to 140 in 1920 and then dropped steadily to 80 in 1975 and to 37 in 2005.[6,7] Thus, the energy efficiency of the United States economy has more than doubled since 1950, as energy use per dollar of GDP in 2004 was only 45% of the 1950 value.

Because the fuel mix has been approximately constant since 1980, the reduction of CO_2 per unit of GDP in **Figure 5** indi-

Table I: World Total Energy Consumption by Region and Fuel, Reference Case, 1990–2030.

Region/ Country	History		Projections				
	1990	2004	2010	2015	2020	2025	2030
OECD North America							
Liquids	40.5	49.2	50.6	53.5	56.2	59.1	62.7
Natural gas	23.2	28.5	31.5	33.5	35.3	36.1	36.8
Coal	20.7	24.1	26.4	27.9	29.7	33.2	36.8
Nuclear	6.9	9.3	9.7	9.9	10.7	10.8	11.0
Other	9.5	9.9	12.2	12.6	13.1	13.8	14.4
Total	**100.8**	**120.9**	**130.3**	**137.4**	**145.1**	**153.0**	**161.6**
OECD Europe							
Liquids	28.4	32.4	32.0	32.2	32.4	32.6	32.7
Natural gas	11.2	19.3	21.8	23.6	24.8	26.3	27.6
Coal	17.6	13.1	13.2	12.8	12.2	11.6	11.5
Nuclear	7.9	9.9	10.2	10.0	9.3	9.3	9.4
Other	4.8	6.3	6.9	7.2	7.5	7.7	8.0
Total	**69.9**	**81.1**	**84.1**	**85.8**	**86.1**	**87.5**	**89.2**
OECD Asia							
Liquids	14.5	17.4	17.3	17.9	18.2	18.6	19.0
Natural gas	2.9	5.3	6.3	6.9	7.3	7.6	8.0
Coal	5.2	9.3	9.8	10.0	10.3	10.7	11.0
Nuclear	2.5	4.0	4.6	5.3	6.0	6.3	6.9
Other	1.6	1.7	1.9	2.0	2.1	2.2	2.3
Total	**26.6**	**37.8**	**39.9**	**42.1**	**43.9**	**45.4**	**47.2**
Total OECD							
Liquids	83.4	98.9	99.9	103.5	106.8	110.3	114.4
Natural gas	37.2	53.1	59.6	64.0	67.5	70.0	72.3
Coal	43.5	46.6	49.4	50.7	52.1	55.5	59.3
Nuclear	17.3	23.2	24.5	25.3	26.0	26.4	27.3
Other	15.9	17.9	21.1	21.8	22.7	23.7	24.7
Total	**197.4**	**239.8**	**254.4**	**265.2**	**275.1**	**285.9**	**298.0**
Non-OECD Europe and Eurasia							
Liquids	19.5	9.9	10.6	11.2	11.8	12.4	12.9
Natural gas	27.5	25.1	27.6	29.9	32.3	34.5	36.6
Coal	15.1	9.0	9.7	10.5	11.3	11.7	
Nuclear	2.5	2.9	3.2	3.7	4.7	5.5	5.5
Other	2.8	2.9	3.6	4.1	4.3	4.6	4.9
Total	**67.2**	**49.7**	**54.7**	**59.4**	**64.4**	**68.7**	**71.5**
Non-OECD Asia							
Liquids	13.9	30.6	38.7	44.0	49.1	54.9	61.5
Natural gas	3.0	8.9	13.3	16.9	20.5	24.7	29.3
Coal	27.2	53.6	70.4	82.9	95.8	107.2	119.2
Nuclear	0.4	1.1	1.6	3.0	4.3	5.5	6.2
Other	3.0	5.7	7.0	7.9	9.1	10.2	11.3
Total	**47.5**	**99.9**	**131.0**	**154.7**	**178.8**	**202.5**	**227.6**
Middle East							
Liquids	7.3	11.6	14.6	15.9	17.2	18.7	20.1
Natural gas	3.8	9.0	11.0	12.8	14.6	15.8	17.1

cates that energy efficiency has improved over time. The improvements in energy efficiency have been roughly the same for poor as for rich, a 33% increase from 1980 to 2002.

The developed nations differ markedly in energy use per dollar of GDP, as shown in **Figure 6**. Canada tops even the United States. In 1980, Japan and Italy were at less than one-half the U.S. level. By 2001, all nations had decreased their energy intensity, with the United States falling a bit faster. Not included in this table is Denmark, whose energy use per dollar of GDP and per capita is about 45% of the U.S. level.

Darmstadter et al.[9] found that about one-half of the difference in energy use is a pure efficiency difference and one-half is a life style difference. Thus, without changing the vehicles we drive, the distance we drive, or the size of our residences, we could reduce our energy use by about 25%, that is, the half of the energy difference due to pure efficiency. The Danish lifestyle is regarded by many as superior to that of the United States. Thus, if residents of the United States were willing to drive smaller, less powerful vehicles; drive fewer miles; live in smaller residences; and generally lead more energy-frugal lives; they could lower their energy consumption by 50%, that is, both the half of the energy difference due to pure efficiency and the half due to a different lifestyle.

Many of the energy decisions that U.S. residents currently make are conditioned by the subsidies that energy has enjoyed. Until the 1970s, there were few rules requiring companies to abate the air pollution emissions from burning fossil fuels. Fuel was sufficiently abundant that prices were extremely low. Coal and oil were extracted with little thought or care for environmental quality. As a result, huge social costs were incurred through environmental degradation and the resulting ill health. For example, the U.S. Environmental Protection Agency (EPA) estimated that abating air pollution between 1970 and 1990 had benefits of $22 trillion compared to

Table I: World Total Energy Consumption by Region and Fuel, Reference Case, 1990–2030. (Continued)

Region/ Country	History		Projections				
	1990	2004	2010	2015	2020	2025	2030
Coal	0.1	0.4	0.5	0.5	0.5	0.6	0.6
Nuclear	0.0	0.0	0.1	0.1	0.1	0.1	0.1
Other	0.1	0.1	0.2	0.2	0.2	0.3	0.3
Total	**11.3**	**21.1**	**26.3**	**29.5**	**32.6**	**35.5**	**38.2**
Africa							
Liquids	4.3	5.7	6.9	7.9	8.9	9.4	10.1
Natural gas	1.5	2.8	3.5	4.3	5.0	5.8	6.6
Coal	3.0	4.1	5.3	5.7	6.0	6.5	6.7
Nuclear	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Other	0.6	0.9	1.1	1.1	1.2	1.3	1.3
Total	**9.5**	**13.7**	**16.9**	**19.2**	**21.2**	**23.1**	**24.9**
Central and South America							
Liquids	7.8	11.5	13.4	15.2	16.8	18.4	19.9
Natural gas	2.2	4.4	5.5	6.5	7.1	7.8	8.5
Coal	0.6	0.8	1.1	1.3	1.5	1.5	
Nuclear	0.1	0.2	0.2	0.3	0.4	0.4	
Other	3.9	5.6	7.4	8.2	9.1	9.9	11.0
Total	**14.5**	**22.5**	**27.7**	**31.5**	**34.8**	**38.0**	**41.4**
Total Non-OECD							
Liquids	52.7	69.3	84.1	94.1	103.8	113.8	124.4
Natural gas	38.0	50.3	61.0	70.4	79.5	88.5	98.1
Coal	45.9	67.9	86.9	100.9	115.1	127.4	139.8
Nuclear	3.1	4.3	5.3	7.2	9.6	11.7	12.4
Other	10.3	15.3	19.3	21.6	23.9	26.3	28.8
Total	**150.0**	**206.9**	**256.6**	**294.2**	**331.9**	**367.8**	**403.5**
Total World							
Liquids	136.2	168.2	183.9	197.6	210.6	224.1	238.9
Natural gas	75.2	103.4	120.6	134.3	147.0	158.5	170.4
Coal	89.4	114.5	136.4	151.6	167.2	182.9	199.1
Nuclear	20.4	27.5	29.8	32.5	35.7	38.1	39.7
Other	26.2	33.2	40.4	43.4	46.5	50.1	53.5
Total	**347.3**	**446.7**	**511.1**	**559.4**	**607.0**	**653.7**	**701.6**

Source: Reference 3.
Units: Quadrillion BTU.

abatement costs of $523 billion; thus, benefits were more than 40 times greater than costs.[10]

The costs of U.S. foreign and defense policies to secure large amounts of inexpensive petroleum have not been charged to the imported energy. Consumers made decisions on what car to buy, what size residence to buy, and what temperature to set the thermostat on the basis of artificially lowered prices. Subsidizing a product encourages its use. Thus, the energy policy of the United States has encouraged energy use beyond what it would have been if the price had reflected full social cost.

A combination of higher demand, increasing oil prices, and environmental regulations has raised the price of energy. Income per capita in developed nations has continued to increase, leading to larger houses, larger cars, more computers, more energy-using appliances, and more airplane flights. Because people have purchased more "things," one would expect to see higher energy consumption per capita, but this did not occur. The principal reason why per capita energy use did not increase is greater energy efficiency. Possible gains in energy efficiency have not been exhausted. Even today, energy use is far below its thermodynamic limits. For example, there are 3,412 BTU (3,600 kJ) per kilowatt-hour of electricity. Since the first dynamos in the 1870s, the efficiency of the best plants converting fossil fuels into electricity has risen from about 3% to almost 60%.

Even current conversion efficiencies leave the opportunity for almost doubling efficiency. In a number of applications, diesel and other small generators can achieve 60–80% efficiency through combined heat and power.[11] The diesel generators produce electricity, and the "waste" heat is used for space heating. The combined heat and power idea eliminates the need for expensive cooling towers to dissipate the waste heat and instead uses it productively. Space heating is usually provided in the developed world by natural gas or fuel oil. The combustion gas is far too hot to use for space and water heating and, either directly or through a heat exchanger, must be mixed with cooler air before it can be used. This mixing is a thermodynamic waste, as work can be extracted from the high-temperature gas, which cools it to temperatures suitable for space and water heating.

As **Figure 1** and **Table I** indicate, energy demand is rising rapidly in India and China, fueled by rapid economic growth. Japan, Korea, and other Asian "tigers" grew rapidly after World War II, but at some point, the growth rate declined to more normal levels. India and China are likely to follow the same trend. The increase in energy use in all economies will be depressed by rising energy prices. High energy prices signal that the source is scarce and encourage builders and other decision makers to substitute capital and labor for energy. A high resource price also begins to impede growth. The forecasts in the table are likely to be high.

Challenges for Materials Science

The vast majority of energy used in the United States and other developed nations comes from fossil fuels. Burning these

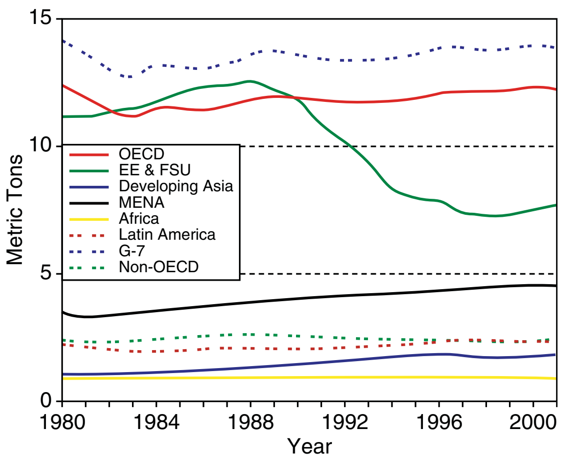

Figure 4. Per capita carbon dioxide emissions for geographical regions worldwide.[5] *Note:* G-7, Canada, France, Germany, Italy, Japan, United Kingdom, and United States; and MENA, Middle East–North Africa.

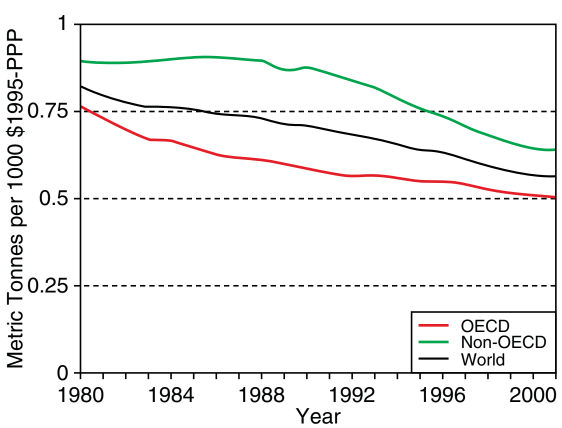

Figure 5. Carbon dioxide emissions per unit GDP for OECD countries, non-OECD countries, and the world through 2001.[5]

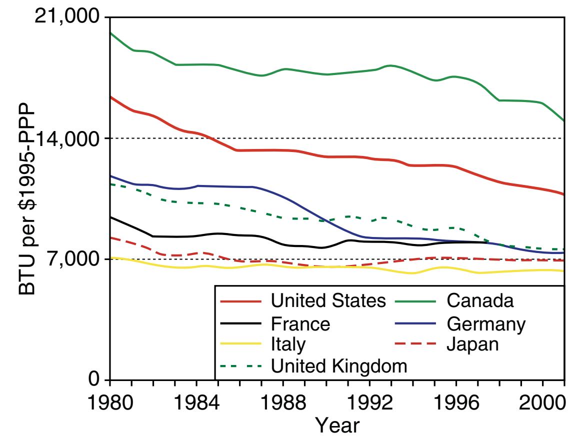

Figure 6. Energy intensity of the G-7 countries through 2001.[8] (1,000 BTU = 1,055 kJ.)

fossil fuels releases CO_2, a greenhouse gas causing global climate change. For much of this century, fossil fuels will continue to be the predominant source of energy, and we will have to find ways to capture and store the CO_2 to prevent, or at least slow, global climate change. For factories and electricity generation plants, one approach is finding materials that will absorb the CO_2 in the flue gas and then release it during regeneration so that the CO_2 can be sequestered underground. Amines are a class of materials that can accomplish this task. Large rewards await materials scientists who can find low cost materials that are more efficient at absorbing CO_2 from flue gas, that can be regenerated cheaply, and that can be used for thousands of cycles.

According to the U.S. Energy Information Agency, in 2006, about 50% of the electricity in the United States was generated from coal, 20% from nuclear power plants, just under 2% from petroleum, 7% from hydroelectric dams, and just over 2% from all renewable sources.[12] As the demand for electricity grows, the burning of coal will have to emit less pollution and lower levels of greenhouse gases and become more efficient. For nuclear power to compete, nuclear plants will have to become less expensive and more efficient (technologies other than light water reactors offer greater efficiency). Renewable energy offers great promise, but the materials challenges are formidable, such as lighter, stronger materials for the blades of wind turbines and better, cheaper materials for photovoltaics, the most environmentally benign generation technology. Each of these technologies requires advances in materials science. For example, fossil fuel use will have to be curtailed without materials that remove pollutant and carbon dioxide emissions.

A second example looks forward to the hydrogen economy. For hydrogen to be an attractive energy carrier, better materials must be found for pipelines to transport the gas without loss and for storage of the gas, especially onboard automobiles. These materials must be inexpensive and long-lived. For storage tanks on cars, the material must also be lightweight and capable of storing large enough quantities to power the vehicle for several hundred miles. Because vehicles are typically garaged in enclosed spaces, the storage tanks can have little or no leakage, as hydrogen is explosive. A further challenge is improving the materials in fuel cells that convert the hydrogen into electricity. To be competitive, the fuel cells must be much less expensive and more efficient than current models and must last the life of the vehicle, about 15 years.

A third example is even more important to the economy and society. Materials are needed that can store electricity much better than current batteries. Owners of cell phones, laptop computers, personal digital assistants (PDAs, also known as handheld computers), digital video disc (DVD) players, and children's toys are frustrated by the limited amount of electricity stored, recharging time, and the weight of the batteries. Electrochemistry has allowed vast improvements over lead-acid batteries, but battery costs are high and the amount of electricity stored per kilogram of battery is frustratingly small.

Indeed, better electricity storage is key to solving major energy/environmental problems. More than 25 states have renewable portfolio standards, mandating the substitution of renewable sources such as wind turbines and solar photovoltaic cells for fossil fuels. In order for these renewable sources to take over a major portion of electricity generation, a large amount of energy storage is needed. For example, the sun can produce electricity for about 6–10 h per day in the United States during the summer. For this amount of solar energy to meet all electricity needs, sufficient electricity storage would be needed so that the 6–10 h of generation would provide electricity for all 24 h. There is currently no low-cost, practical way of storing so much electricity. Moreover, a hurricane or other large storm could interrupt solar electricity generation for days, mandating much larger storage systems in practice.

More daunting than electricity storage for solar electricity is storage for wind turbines. The wind might not blow when electricity is wanted. Indeed, the amount of wind tends to be lower during the hottest summer hours when the electricity load is the greatest. At a good wind site in the eastern United States, a wind turbine generates energy about one-third of the time. If wind were to supply all of the nation's electricity, electricity storage would have to be three to five times the capacity of the wind farm in order to provide power for 24 h per day with some spare capacity for the days when the wind produces little or no electricity. Although current batteries can store electricity, it would be prohibitively expensive to have sufficient batteries to store so much electricity.

One last challenge for electricity storage is "plug-in" hybrid or all-electric vehicles. A battery that could power a vehicle for 30–40 miles (48–64 km) and be recharged from an electricity outlet would save about two-thirds of gasoline use.[13] Because only about 2% of electricity is generated from petroleum, if all automobiles and light trucks were plug-in hybrids, more than one-half of oil imports could be eliminated. If a battery were capable of powering the vehicle for 150 miles (240 km) and could be recharged from an outlet in 5–10 min, it might be possible to eliminate the use of gasoline in cars and light trucks. These vehicle batteries pose an extreme challenge for materials scientists. Vehicle weight is critical for fuel economy. An ideal 30–40 mile (48–64 km) battery for a plug-in hybrid would weigh no more than about 200 pounds (90 kg); would cost no more than a few thousand dollars; would last the 15-year lifetime of the vehicle; and would be safe, nontoxic, and easily recycled.

Limitations in current materials constrain improvements in energy and environment. Society and the economy have much to gain from materials research and development in these areas. The challenges are formidable, but the rewards for achieving them are large.

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13. P. Jaramillo, S. Samaras, *Emissions from Coal-to-Liquids and Plug-in Hybrids* (Working paper, Electricity Industry Center, Carnegie Mellon University, Pittsburgh, PA, 2007). □