CHAPTER 3

Energy Reserves and Renewable Energy Sources

During industrial expansion, we can rapidly deplete available resources. This has occurred for petroleum on U.S. soil. Proven, recoverable oil reserves in the United States would only power our thirst for oil for three years if cut off from oil imports. Technology can meet the challenges of dwindling U.S. oil reserves but only by switching to the abundance of other energy forms and reserves. This energy is available in three forms: fossilized solar energy, nuclear energy, and recent solar energy.

Fossil Fuel Reserves

The "fossil" designation of certain fuels implies that the fuel energy content originates from prehistoric vegetation or organisms. Fossil fuels are the most commonly used energy source to drive our machines. Unlike wind and sunlight, which are dispersed in low concentrations across the surface of the Earth, commonly used fossil fuels tend to be concentrated at locations near the Earth's surface. Where these are easily accessible, we are able to collect them with great efficiency. Fossil fuel sources include the following:

- Coal
- Petroleum
- Heavy oil
- Oil sands
- Oil shale

- Methane hydrates
- Natural gas

In Wyoming, some coal seams are 40 feet thick and less than 100 feet underground. In the Middle East, hundreds of barrels per day of crude oil can flow from a single well under its own pressure. Each source provides abundant energy.

Coal,[1] petroleum,[2] and natural gas[3] are accessible fossil fuels and easy to use (see box, "Petroleum and Gas"). By far, they are today's most popular fuels. Figure 3-1 summarizes the known accessible reserves of these fuels in the entire world and in the United States. World recoverable reserves for coal, natural gas, and petroleum are 2.5E+19 (25 billion billion), 6.9E+19, and 5.3E+18 Btus.[4] For coal, the total estimated reserves are about a factor of ten higher than the estimate for recoverable reserves.[5]

In the year 2000, the United States consumed 19.7 million barrels of petroleum per day (see Chapter 2) or 3.8E+16 Btus per year. This consumption would deplete known U.S. petroleum reserves in about 3 years and estimated U.S. petroleum reserves in about 7.6 years. These statistics are summarized in Table 3-1.

Petroleum represents about 53% of the total annual U.S. energy consumption.[i] The U.S. total energy consumption would

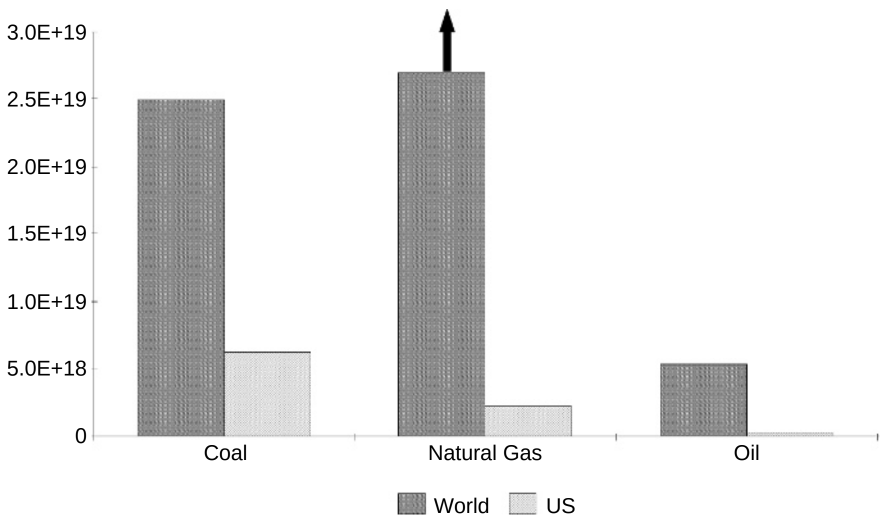


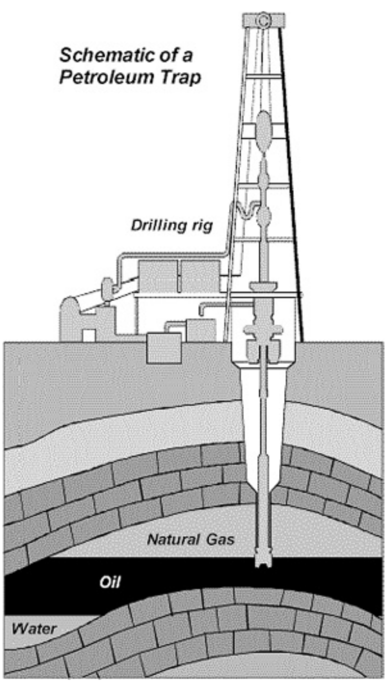
FIGURE 3-1. Summary of world and U.S. fuel reserves in Btus.

[i] The total U.S. energy consumption is about 7.1E+16 Btus per year.

TABLE 3-1
Comparison of energy reserves and rates of consumption.

Energy Description	*Amount (Btus)*	*Amount (as indicated)*
World Recoverable Coal Reserves	2.5E 19	
World Recoverable Natural Gas Reserves	6.9E 19	
World Recoverable Petroleum Reserves	5.3E 18	
U.S. Petroleum Consumption (year 2000)	3.8E 16	19.7E 6 barrels
U.S. Petroleum Consumption divided by U.S. Known Petroleum Reserves		3 years
U.S. Total Recoverable Coal Reserves Divided by U.S. Total Energy Consumption		90 years

deplete U.S. estimated reserves of petroleum in four years. Natural gas would last 30 years, and coal would last 90 years. Coal can be used for much more than electrical power production (see box, "Strategic Technologies"). World natural gas reserves would last 1,000 years if they were used only to meet U.S. consumption. Figure 3-1 illustrates the relative magnitude of these reserves.



Petroleum and Gas—from the Ground to the Refinery

The inserted image[6] illustrates a typical petroleum reservoir and drilling used to recover that petroleum. A rock cap has kept the reserve isolated from atmospheric oxygen for millions of years. Since the petroleum is lighter than water, it floats above water aquifers. Petroleum gases, including natural gas, are the least dense material in the formation and are above the oil. Drilling and inserting a pipe into the petroleum reserve allow recovery. Oil reserves recovered by conventional land drilling applications are typically several hundred feet to about one mile deep.

Estimated energy reserves in heavy oil, oil sands, oil shale, and methane hydrates dwarf known reserves in coal, natural gas, and petroleum. One evolutionary route to form these three reserves includes the advanced stages of petroleum decay. Petroleum contains a wide range of hydrocarbons, ranging from the very volatile methane to nonvolatile asphaltines/tars. When petroleum is sealed securely in rock formations, the range of volatility is preserved for millions of years or converted to methane if buried deeper, where it is converted by geothermal heat.

Strategic Technologies of the 21st Century

A few technologies stand out as logical extensions of current technology that have both economic and strategic value. These technologies generally require greater coordination than first generation technologies, and they are based on adding value to abundant indigenous resources. Uranium reprocessing is a strategic technology for electrical power generation.

Coal and biomass qualify as abundant local resources that could be better utilized. The solid fuel refinery uses these feed stocks to supply an array of conversion and synthesis processes, including electrical power generation, production of liquid fuels, and production of chemicals like ammonia. The synthesis gas pipeline is based on much the same concept as the solid fuel refinery, but in the synthesis gas pipeline a pipe network is fed mixtures of hydrogen and carbon monoxide from several source locations. Likewise, the pipeline is used as a feed stock for chemicals and fuel by many processes. Two technologies stand out to tap into these resources (see "Option 1" and "Option 2" boxes).

If the rock overburden is fractured, either due to erosion of rocks above the formation or simply due to the weak or porous nature of the rock, the more volatile components of petroleum escape. This leaves less-volatile residues in the forms of heavy oils, oil sand, and oil shale.

Heavy oils are volatile-depleted deposits that will not flow at reservoir conditions but need assistance for recovery. Oil sand liquids are heavier than heavy oils—typically not mobile at reservoir conditions, but heat or solvents can make the oil flow through the porous rock. Oil shales are usually immobile and present in rocks that do not allow oil flow. Unlike the oil in oil sands that can be removed in situ or with low amounts of solvent and heat, the oil in shale tends to be very difficult to remove.

This makes oil shales more difficult to recover than oil sand. Unlike coal, which is a concentrated fossil fuel, oil shale is best characterized as a relatively nonvolatile oil dispersed in a shale. World reserves are estimated to be 600 to 3,000 times world crude oil reserves.[7] Lower estimates specific to the western United States place reserves at two to five times known world oil reserves.[8]

Option 1: Synthesis Gas Pipeline

In the solid fuel refinery, the synthesis gas generation can be separated from the other processes. This represents a potential added cost to recovering the heat from the synthesis, which is not required in a solid fuel refinery. The synthesis gas pipeline has this drawback, plus the expense of the pipeline, but the benefits are many.

Reduced transportation costs (pipeline versus railroad) are an advantage, as well as the ease of disposal of coal ash at the mining location as landfill to replace space created by removing the coal. Sulfur removal from the coal would be easier using this approach. This would allow the reopening and increased use of several minefields across the country that contain high-sulfur coal.

The synthesis gas will allow electrical power generation from coal approaching 50% thermal efficiency, which is about 10% better than direct firing coal. Furthermore, customers are likely to use this option, since they would not have the burden of building a gasification facility. The synthesis gas would have all the advantages of natural gas, but it would presumably be less costly on an equal energy basis.

A synthesis gas pipeline would allow smaller companies and entrepreneurs to enter the energy big business. Opportunities would exist both for production of synthesis gas (potentially from biomass or municipal solid waste) and use of the gas from the pipeline in a large array of processes. The pipeline would make it possible for companies to enter business with smaller investments and easy feedstock acquisition.

Heavy oil reserves in Venezuela are estimated to be from 0.1 trillion barrels[9] to 1 trillion barrels.[10] These heavy oils are generally easier to recover than oil sands and much easier to recover than oil from oil shale. The United States, Canada, Russia, and Middle East also have heavy oil reserves totaling about 0.3 trillion barrels[11] (lower side of estimates). In all, the heavy oil reserves are estimated to be slightly greater than all the more-easily recovered conventional crude oil reserves.

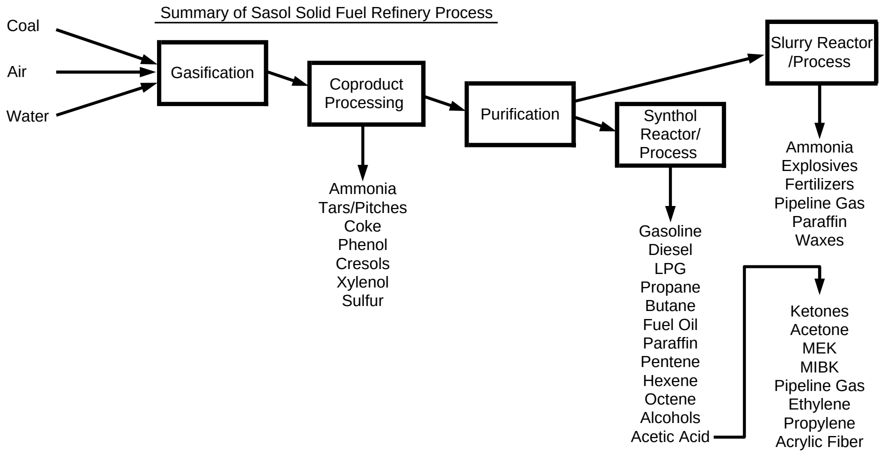
Surface reserves of oil sands have been mined and converted to gasoline and diesel since 1969 in Alberta, Canada. Production costs are about $20 per barrel.[12] These supply about 12% of Canada's petroleum needs. The sands are strip-mined and extracted with hot water. Estimated reserves in Alberta are 1.2–1.7 trillion barrels with two open pit mines now operating.[13] Other estimates put oil sand reserves in Canada, Venezuela, and Russia at about 3, 3, and 0.6 trillion barrels. Estimates approximate 90% of the world's heavy oil (and oil sand) to be in Western Canada and Venezuela.[14] Cumulatively, oil sand reserves are six to ten times proven conventional crude oil reserves. (Conventional crude oil reserves are reported at 1 trillion barrels.)

Option 2: Solid Fuel Refinery

A solid fuel refinery capitalizes on the strengths of several processes to overcome the weaknesses of each process to produce much higher final conversion efficiencies. For example, electrical power generation does not effectively use low-temperature steam and flue gases, but it produces large quantities of these gases.

For Fischer-Tropsch synthesis, conversion of the last bit of hydrogen and carbon monoxide to liquid fuels is considerably more expensive than the initial conversion of fresh feed. In a solid fuel refinery, the residual carbon monoxide and hydrogen are suitable for driving a gas turbine to generate electricity. These residual gases left from liquefied fuel production are used for electrical power generation that is more efficient than a coal-fired power plant.

Ammonia is an important chemical produced in a solid fuel refinery because of the energy intensity of the ammonia production process and its value as a fertilizer. Building one big gasifier to feed several processes brings an important economy of scale for this important step.



Solid fuel refineries are a reality in South Africa, as illustrated by the flow diagram. A large array of chemicals are produced. The overall process makes the best use of coal resources for supplying many useful products.

If methane escapes from an underground deposit (due to porous rock or erosion of overburden) and comes in contact with a combination of increased pressure, water, and cold temperatures, methane hydrate is formed. Methane hydrate is ice that contains methane and is stable below the freezing point of water as well as at temperatures slightly warmer than the freezing point of water at high pressure. Conditions are right for the formation of methane hydrates on the sea floor (under a few hundred feet of seawater, where the temperature is relatively constant at the temperature of maximum water density, 4°C; this is true even in the Caribbean) and in the Arctic permafrost. In addition to formation mechanisms involving petroleum decay, methane is commonly formed directly from biomass—both geological and recent biomass methane can form hydrates.

Methane hydrate reserves are not presently recovered. Countries like Japan have great interest in the potential of this technology because of the lack of natural fossil fuel reserves in the country and the large coastal water areas. In the United States, methane hydrates have received the attention of congressional hearings where reserves were estimated at 400 million trillion cubic feet (200,000 trillion cubic feet of gas (Tcf) in reserves under the jurisdiction of the United States). In the most conservative interpretation, these hydrates have enough energy to last maybe 5,000 years.

Natural gas emissions from these reserves occur naturally, so the methane greenhouse effect from this source will occur regardless of whether or not we use the energy. If we burn the natural gas from these emissions, the resulting carbon dioxide would have about one-tenth of the greenhouse effect of the equivalent methane release. The release of methane from methane hydrates on the sea floor may have contributed to the end of many of the ice ages. During ice ages, lower sea levels reduced the pressure on the sea floors. This lower pressure would lead to methane release.[15]

The trick to reducing natural methane emissions is to mine and recover those reserves that are most likely to release naturally. Most hydrate mining research involves changing the temperature and pressure at the solid reserve location to cause the methane hydrates to melt or sublime and then to recover the methane that is evolved. Experts at the congressional hearing agreed that *Alaska's North Slope was the most likely candidate for initial research because of its relative easy access (compared to the deep-water Gulf of Mexico) and in-place infrastructure*.[16]

In some instances, natural gas reserves are below ground and in equilibrium with methane hydrate reserves. When the natural gas is recovered, the methane hydrates melt, resupplying the gas in the reserve for easy recovery.

Table 3-2 summarizes the energies available in recoverable fuels. All of these fuels are in concentrated deposits, with the exception of uranium. The uranium availability includes recovering uranium from sea waters, which is possible but costly compared to today's prices. The numbers approximate the magnitudes of the different reserves relative to conventional crude oil reserves.

Estimating energy reserves has historically been inaccurate. For example, in the 1980s when the oil-producing countries shifted from a mentality of "creating the perception of oil shortfalls" to setting production quotas based on "countries reported reserves," the reported reserves increased dramatically. Likewise, reported coal reserves decreased by a factor of 10 from 1980[17] to 2002[18] due to redefinitions of recoverable reserves and the influence of oil companies on U.S. policy and U.S. Department of Energy positions.

Qualitatively, the image portrayed by Table 3-2 is correct. The costs of fuels reflect this. Petroleum ($45–$75 per barrel) and natural gas cost $9.00–$15.00 and $6.00–$12.00 per MBtu, respectively.

TABLE 3-2
Relative abundance of recoverable fuels.

U.S. Petroleum	1/20 X
World Petroleum	1 X
World Recoverable Coal	5 X
World Recoverable Heavy Oil and Oil Sands	10 X
World Recoverable Natural Gas	15 X
World Recoverable Oil Shale	>500 X
World Methane Hydrates	>5,000 X
World Recoverable Uranium	50,000 X

Coal costs about $1.20–$1.40 per MBtu. Uranium costs $0.62 per MBtu when 3.4% is fissioned or $0.062 per MBtu if a fission of 35% is assumed.

The following uses of these reserves are consistent with recent trends:

- Major oil corporations will likely progressively tap into oil sands and heavy oil as the reserves of petroleum are depleted. The corporations will likely be able to meet petroleum needs for several decades in the progression; however, this progression will likely occur to maintain corporate profit, will result in huge trade deficits, and may be at the expense of continuous military activity.
- Natural gas use in the United States is likely to follow the course of petroleum. The depletion of U.S. reserves will lead to increasing reliance on imports.
- Coal will continue increased use in electrical power generation. However, its high rate of carbon dioxide generation and limited

recoverable reserves will dampen its expansion relative to 1970s estimates that stated centuries of abundance. New technology is likely to bring a greater portion of the total coal reserves into the "recoverable" coal reserves category.
- Energies in oil shale are unlikely to be realized due to the high energy and cost of recovery.
- Methane hydrate recovery is uncertain because not enough is known about safe methods for its recovery, and the extent of reserves of "recoverable" methane hydrates depends on this technology.

Impacting technologies likely to develop in the next 30 years include 100% nuclear fission of nuclear fuel for abundant electricity, hybrid vehicles that are partially rechargeable with grid electricity, and chemicals and fuels made from biomass. Closed cycle nuclear fuel cycles that use all of the energy in uranium (including U-238) include reprocessing of spent nuclear fuel and the concentration of fission products so that the volume of waste is 100 times less than if the fuel rods were directly placed in repositories. These are the technologies that can change the rules, can deliver sustainability, and can promote economic prosperity by eliminating the need to import oil and natural gas.

Cosmic History of Fossil Energy Reserves

Similar to the fossilized bones of a dinosaur, fossil fuels are the remains of plants and microscopic organisms. Their compositions reveal a history going back hundreds of millions of years; however, the history of the energy in these fuels does not start there. This history goes back to the origin of the universe. An understanding of the dominant role nuclear energy has played in the history of energy helps us understand how nuclear energy will always be part of the energy mix we use.

What Is Permanence?

The Permanence Scale in Figure 3-2 is the binding energy in MeV for each nucleon (a proton or neutron) in the nucleus of an atom. The most stable atoms are those with the highest binding energy per nucleon. The nucleon-binding energy is plotted against the atomic mass number. The maximum binding energy per nucleon occurs at mass number 54, the mass number for iron. As the atomic mass number increases from zero, the binding energy per nucleon also increases because the number of protons (with positive charge) increases, and protons strongly repel each other. The binding energy of the neutron (no charge) holds the nucleus of the atom together. The atomic mass number for each atom is approximately the mass of the protons and neutrons in the nucleus, since the electrons (equal to the number of protons) have a mass that is about 1/1,837 that of a nucleon.

Above a mass number of about 60, the binding energy per nucleon decreases. Visualize the large atom nucleus as many protons try to get away from each other, with a much larger number of neutrons holding that nucleus together. The common isotope of iron-56 (about 92% of the mass of natural iron) has 26 protons and 30 neutrons. The common isotope of uranium-238 (about 99.27% of the mass of natural uranium) has 92 protons and 146 neutrons. The iron nucleus is very stable. The uranium-238 isotope does spontaneously decay, but it will take about 4.5 billion years for one-half of a lump of pure U-238 to decay, so it is practically a stable isotope.

An additional comment: The nucleon-binding energy increases as the atomic mass decreases from 260 to 60. This is the primary reason for the energy release in the fission process that makes nuclear reactors work. Since the forces in the nucleus of large atoms are so carefully balanced, a small energy addition (a low-energy neutron entering the nucleus) will cause the large forces acting between the protons to become unbalanced, and the nucleus comes apart (flies apart), releasing lots of energy. These large atoms are the fuel for nuclear reactors. The strong binding energies of the smaller atoms lead to the permanent end point of the natural isotope decay processes.

The arrays of different elements in our planet, the solar system, and the galaxy reveal their history. Hydrogen is the smallest of the atoms assigned an atomic number of one. Physicists tell us that at the birth of the universe, it consisted mostly of hydrogen. Stars converted hydrogen to helium, and supernovas (see the box "Supernovas") generated the larger atoms through atomic fusion.

Atoms are identified based on the number of protons (positively charged subatomic particles). Since both hydrogen and helium are smaller atoms than the nitrogen and oxygen in the air, the Goodyear blimp (filled with helium) and the Hindenburg zeppelin (filled with hydrogen) floated in air.

Helium has 2 protons, lithium has 3 protons, carbon has 6 protons, and oxygen has 8 protons. The number of protons in an atom is referred to as the "atomic number" of the atom. Atoms are named and classified by their atomic number. Atoms having between 1 and 118 protons have been detected and named (see the box "Making New Molecules in the Lab"). The atomic mass is the sum of the mass of neutrons, protons, and electrons in an atom—the atomic mass and the atomic spacing determines the density of materials.

Protons are packed together with neutrons (subatomic particles without a charge) to form an atom nucleus. There are more stable and less stable combinations of these protons and neutrons. Figure 3-2 illustrates the permanence of nuclei as a function of the atomic mass number (the atomic mass is the sum of the protons and neutrons). Helium 3—abbreviated He,3—is shown to have a lower permanence than He,4. Two neutrons simply hold the two protons in He,4 together better than one neutron in He,3. In general, the number of neutrons in an atom must be equal to or

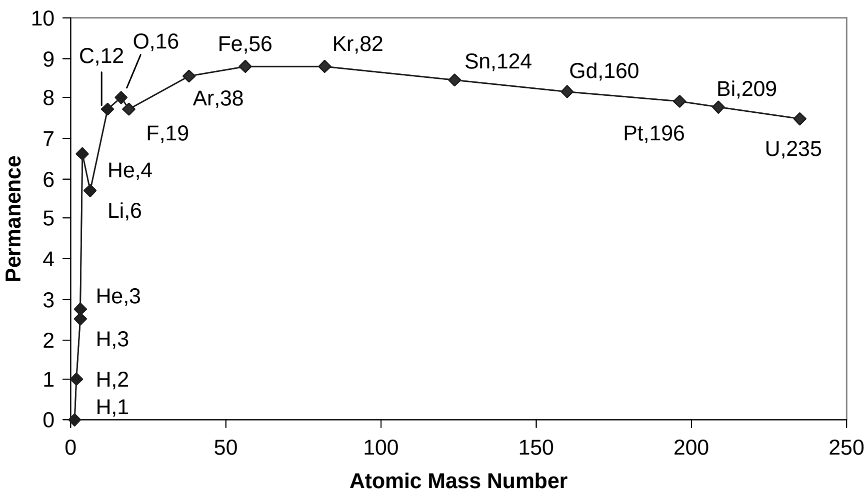


FIGURE 3-2. Impact of atomic mass number on permanence of atoms. H is hydrogen, He is helium, Li is lithium, C is carbon, O is oxygen, F is fluorine, Ar is argon, Fe is iron, Kr is krypton, Sn is tin, Gd is gadolinium, Pu is plutonium, Bi is bismuth, and U is uranium.

greater than the number of protons, or that atom will disintegrate into more stable combinations of protons and neutrons.

The wealth of information in Figure 3-2 explains much about the chemistry of our planet. For example, why do hydrogen atoms combine to form helium instead of breaking apart to form hydrogen atoms? Figure 3-2 illustrates that the "permanence" is greater for He,4 than for hydrogen (H,1). In nuclear reaction processes, atoms tend to move uphill on the curve of Figure 3-2 toward more stable states. In Chapter 10, the concept of atomic stability will be discussed in greater detail, and the term "binding energy" will be defined and used in place of "permanence."

Supernovas—The Atomic Factories of the Universe

Astronomers have observed "lead stars" that produced heavier metals like lead and tungsten. Three have been observed about 1,600 light-years from Earth. To paraphrase a description of the process:

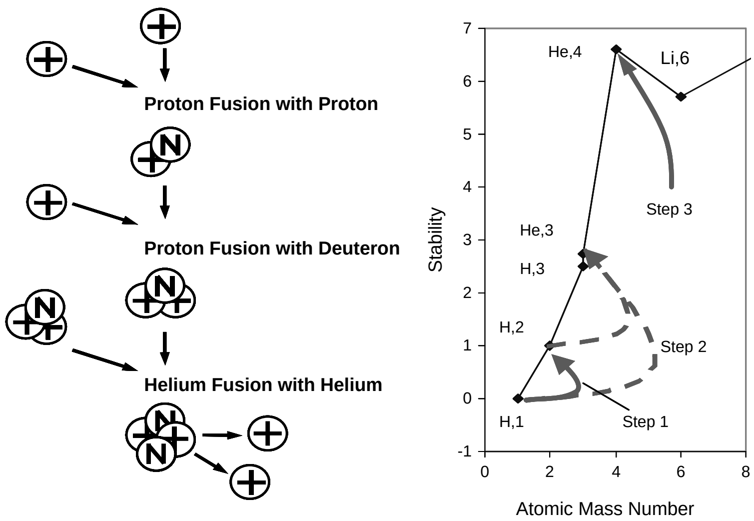
Stars are nuclear "factories" where new elements are made by smashing atomic particles together. Hydrogen atoms fuse to create helium. As stars age and use up their nuclear fuel, helium is fused into carbon.

Carbon, in turn, is fused into oxygen, and the process continues to make heavier elements until a natural limit is reached at iron. To make elements heavier than iron, a different system is needed that adds neutrons to the atomic nuclei. Neutrons are a kind of atomic "ballast" that carry no electric charge.

Scientists believe there are two places where this can occur: inside very massive stars when they explode as supernovas and more commonly, in normal stars right at the end of their lives before they burn out.

To make atomic transitions to more permanent/stable atoms, extreme conditions are necessary (see the box "Supernovas"). On the sun, conditions are sufficiently extreme to allow hydrogen to fuse to more stable, larger molecules.[19] In nuclear fission reactions in a nuclear power plant or in Earth's natural uranium deposits, large molecules break apart to form more stable smaller molecules.

Each atomic event is toward more stable combinations of protons and neutrons, and this process releases energy.



From Hydrogen to Helium

The most abundant atom in the universe is hydrogen. Hydrogen is the fuel of the stars. The diagram[20] illustrates how four protons interact to produce a new stable molecule: helium. Considerable energy is released in the process—about 25 MeV of energy for every helium atom formed (570 million Btus per gram helium formed).

Figure 3-3 is the starting point for qualitative understanding the history of energy. Nuclear reactions are where the history of energy begins. The story of the history of energy goes something like this: Once upon a time, long ago—about 15 billion years—there was a big bang. From essentially nothingness, in an infinitely small corner of space, protons and helium were formed. Carbon, iron, copper, gold, and the majority of other atoms did not exist.

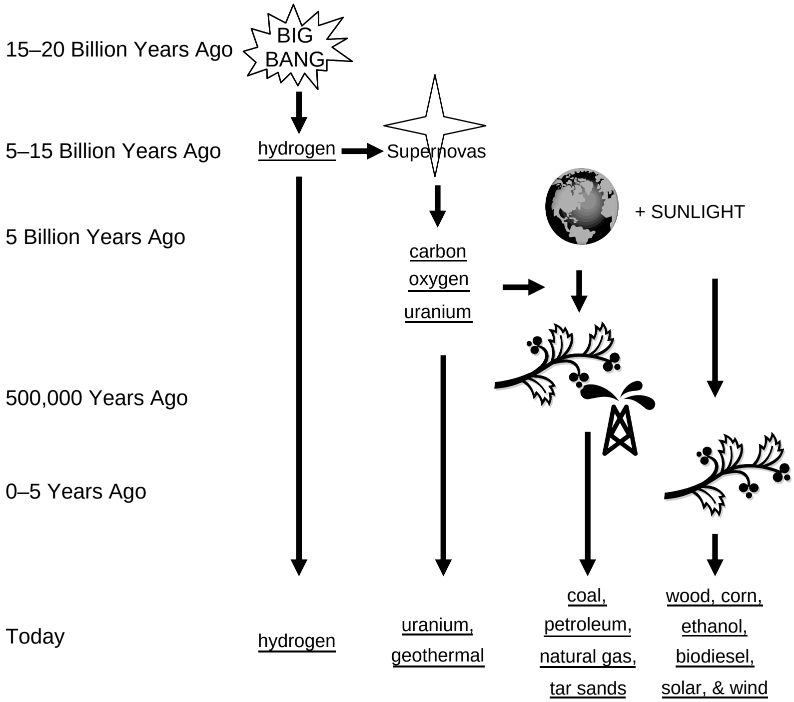
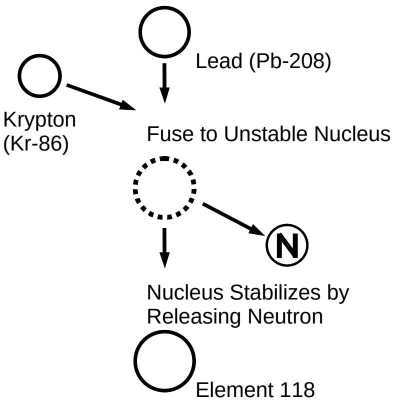


FIGURE 3-3. The history of energy.

Unimaginably large quantities of hydrogen and helium clustered together to form stars. The most massive of these stars formed supernovas. Fusion conditions were so intense in these supernovas that atoms of essentially all known atomic numbers were formed. Hence, carbon, oxygen, iron, copper, gold, and the vast array of atoms that form solid objects around us were formed.

Uranium was also formed along with atoms larger than uranium. The largest of these atoms rapidly fell apart to form more stable molecules. Uranium and plutonium have intermediate stability. They could be induced to fall apart but were stable enough to last for billions of years without spontaneous decomposition.

The spinning masses continued to fly outward from the big bang. As time passed, localized masses collected to form galaxies, and within these galaxies, solar systems, stars, planets, asteroids, and comets formed.



Making New Molecules in the Lab

On small scales, scientists are able to make new molecules similar to the way in which supernovas combine two smaller molecules to form a larger molecule. As illustrated in the figure, krypton and lead combine to form a compound nucleus. This nucleus is very unstable and rapidly degrades to a more stable atom indicated as Element 118.[21]

This work was performed at the Lawrence Berkeley National Lab. During this synthesis, two atoms are joined to actually form a less stable molecule. This is possible in a particle accelerator that puts kinetic energy (high speed) into the krypton. This high speed provides the extra energy needed to fuse the nuclei. The atomic rearrangement resulting in the release of a neutron helps lock in a final element that is stable. High atomic number atoms are unstable and not found in nature.

It is here where energy and the universe as we know it began to take form. We are just beginning to understand the processes of the stars and supernovas to tap into the vast amounts of binding energy in the atom. The atomic binding energy available in one pound of uranium is equivalent to the chemical binding energy present in 8 million pounds of coal.[ii]

Nuclear Energy

In principal, nuclear energy is available in all elements smaller than iron through nuclear fusion and all elements larger than iron through nuclear fission. Iron is on the top of the permanence curve so it is one of the most abundant elements. While all other atoms

[ii] 12,000 tons per day (Ch. 4, Steam Turbine Section) = 365 days/year × 40%/30%/(750 kg × 1 ton/~1,000 kg).

can degrade to iron, iron does not degrade. When most of the nuclear energy of the universe is expended, it will consist mostly of iron and elements of similar atomic number (all being stable).

In general, the largest atoms are the most likely—given enough time—to undergo nuclear decays such as the release of an alpha particle (a helium atom). Atoms larger than uranium (see[22]) have undergone fission to the extent that they can no longer be found on Earth. The amount of U-238 on Earth today is slightly less than half of what was present at Earth's formation. The amount of U-235 on Earth today is less than 1% of what was present at Earth's formation.

Of interest to us is the ability to perform these nuclear processes in a controlled and safe manner, because the nuclear binding energy can be used to produce electricity. The energy released as protons, neutrons, and atoms combines and rearranges in the progression to higher "binding energy." We are able to use nuclear fission on a practical/commercial scale with one naturally occurring element: uranium. We could perform fission on elements larger than uranium, but these are not readily available. In the H-bomb, we have demonstrated an ability to tap the energy of fusion for massive destruction, but use of fusion for domestic energy production is much more difficult. Practical nuclear fusion methods are an area of active research.

The only practical nuclear energy sources today are nuclear fission of uranium in nuclear reactors and the recovery of geothermal heat produced by nuclear decay under the surface of Earth (occurring continuously). Uranium is the primary fuel for both of these processes.

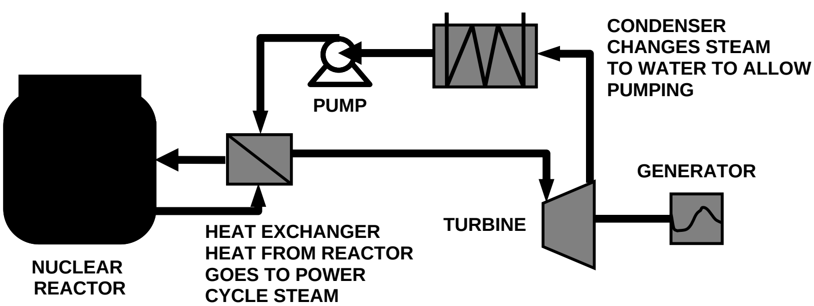
At 18.7 times the density of water, uranium is the heaviest of all the naturally occurring elements (the lightest is hydrogen; iron is 7.7 times the density of water). All elements (as defined by the number of protons in the nucleus) occur in slightly differing forms known as *isotopes*. These different forms are caused by the varying number of neutrons packed with the 92 protons in uranium's nucleus. Uranium has 16 isotopes, only two are stable. Most (99.3%) of natural uranium is composed of uranium-238 (U-238, 238 is the sum of neutrons and protons) and U-235, about 0.71% of natural uranium.

U-235 is slightly less stable than U-238 and when enriched to 3% to 8% can be made to release heat continuously in a nuclear reactor. Enriched to 90% U-235 and the sudden release of large amounts of energy becomes a nuclear bomb. We have mastered the technology to perform both of these processes. The U-238 decays slowly with about 2 kilograms of uranium decaying to 1 kilogram of uranium and slightly less than 1 kilogram of fission products in about 4.5 billion years. About half of the U-238 present when Earth was formed (and >99% of the U-235) has decayed, keeping the Earth's interior a molten metal core.[23]

U-235 decays faster than U-238. We are able to induce the fission of U-235 by bombarding it with neutrons. When one neutron enters the U-235 nucleus to form U-236, it breaks apart almost instantly because it is unstable. It breaks apart to form the nucleus of smaller atoms plus two or three neutrons. These two or three neutrons can collide with U-235 to produce another fission in a sustained chain reaction.

Nuclear fission occurs when the nucleus of an atom captures a neutron and breaks apart expelling two or three neutrons. The U-235 continuously undergoes fission (fission half life of 1.8E 18 years, alpha-decay half life of 6.8E 8 years) that proceeds slowly because there is so little U-235 in the metal; most of the emitted neutrons are lost with only a few producing fission. The exception was the natural nuclear reactor that formed in Oklo, Gabon (Africa), about 2 billion years ago. This occurred when the concentration of U-235 in ore at Oklo was high enough to cause a chain fission of the U-235 leading to lower-than-normal U-235 concentrations and trace plutonium in the deposits today.

Modern Nuclear Reactors in the United States



Modern nuclear power plants[24] use a pressurized water reactor to produce the thermal energy to produce the steam to drive a turbine and generate electricity. The fuel is 3% to 4% U-235 enriched uranium oxide pellets sealed in tubes that are held in racks in the reactor pressure vessel. This maintains the geometry of the reactor core. The water that removes the heat from the core leaves the reactor at about 320°C, and it would boil at a pressure of about 70 atmospheres (850 psi). The pressure in the reactor vessel is held at 150 atmospheres (2,250 psi), so it never boils. This hot water is pumped to a heat exchanger, where the steam to drive the turbines is produced. The high-pressure reactor cooling water will always contain small amounts of radioactive chemicals produced by the neutrons in the reactor. This radioactivity never gets to the steam turbine where it would make it difficult to perform maintenance on the turbine and steam-handling equipment.

Large pressurized water reactors produce about 3,900 megawatts of thermal energy to produce about 1,000 megawatts of electric power. The reactor core contains about 100 tons of nuclear fuel. Each of the nuclear fuel racks has places where control rods can be inserted. The control rods are made of an alloy that contains boron. Boron metal absorbs neutrons, so with these rods in position, there will not be enough neutrons to initiate a chain reaction. When all of the fuel bundles are in position and the lid of the pressure vessel sealed, the water containing boric acid fills the pressure vessel. The control rods are withdrawn, and the boron water solution still absorbs the neutrons from U-235 fission. As the water circulates, boric acid is slowly removed from the water and the neutron production rate increases; the water temperature and pressure are closely monitored. When the neutron production rate produces the rated thermal power of the reactor, the boron concentration in the water is held constant. As the fuel ages through its life cycle, the boron in the water is reduced to maintain constant power output.

If there is an emergency that requires a power shutdown, the control rods drop into the reactor core by gravity. The control rods quickly absorb neutrons, and fission power generation stops. The radioactive fission products in the fuel still generate lots of heat, as these isotopes spontaneously decay after fission stops. Water circulation must continue for several hours to remove this radioactive decay heat.

Our use of nuclear fission to make a bomb is based on an uncontrolled chain reaction. A neutron chain reaction results when, for example, two of the neutrons produced by U-235 fission produce two new fission events. This will occur when nearly pure U-235 is formed into a sphere that contains a critical mass: about

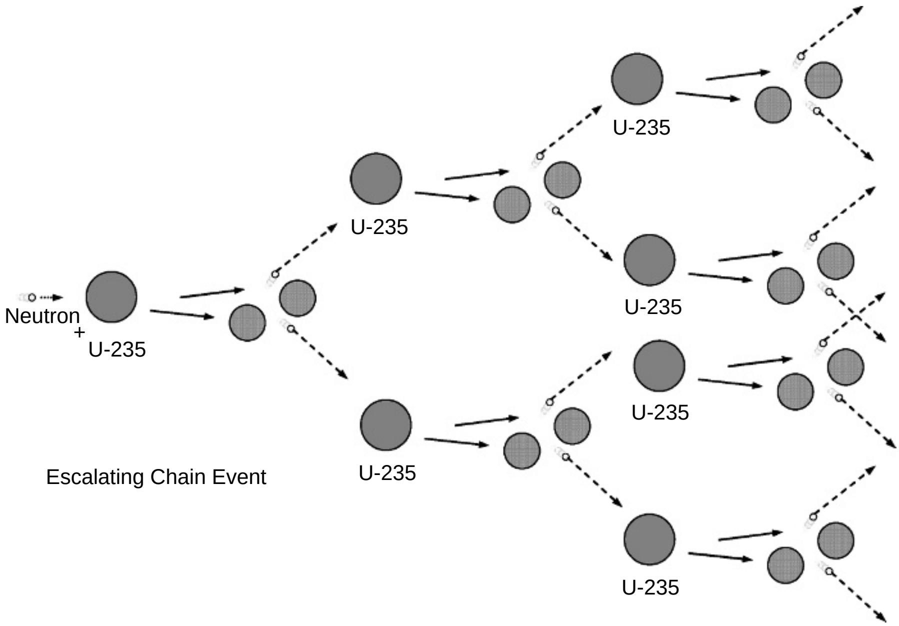


FIGURE 3-4. Escalating chain reaction such as in a nuclear bomb.

60 kilograms of metal. Then in each interval of 10 billionths of a second, the number of fission events grows from 1, 2, 4, . . . 64, . . . 1,024, 2,048, . . . as illustrated by Figure 3-4. The transition from very few fission events to an uncountable number occurs in less than a microsecond. The enormous energy released in this microsecond is the source of the incredible explosive power of a nuclear fission bomb.

This escalating chain reaction is to be distinguished from the controlled steady-state process as depicted by Figure 3-5. In a controlled steady-state process, a nearly constant rate of fission occurs (rather than a rapidly increasing rate) with a resulting constant release of energy.

The first nuclear bomb used in war exploded over Hiroshima, Japan, was a U-235 bomb. Two hemispheres containing half of the critical mass are slammed together with conventional explosive charges. In the resulting nuclear explosion, about 2% of the U-235 mass underwent fission. Everything else in the bomb was instantly vaporized. The fireball and the explosion shock wave incinerated and leveled a vast area of Hiroshima. This is the legacy of nuclear energy that indelibly etched fear into the minds of world citizens. The second explosion at Nagasaki was a plutonium bomb,

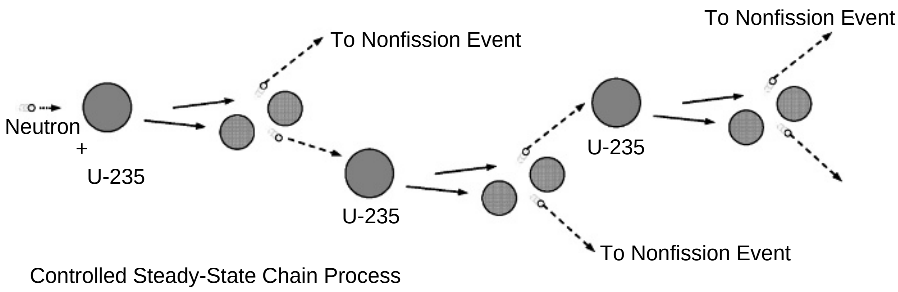


FIGURE 3-5. Controlled steady-state chain nuclear fission such as in a nuclear reactor.

followed by the development and testing of even more powerful and fearsome nuclear weapons during the Cold War period, adding to this legacy of fear.

For a nuclear bomb, the rapid chain reaction depicted by Figure 3-4 is competing with the tendency for the melting/vaporizing uranium to rapidly splat over the surroundings. This "splatting" action tends to stop the chain reaction by separation of small pieces of uranium. Weapon's grade U-235 is typically at least 80% U-235; higher purities give increased release of the nuclear energy (more fission and less splatting).

The enormous energy available from U-235 in a very small space led U.S. naval technologists to consider using nuclear energy to power submarines. The task is to configure the nuclear fuel (U-235 and U-238) so that exactly one of the neutrons produced by a U-235 fission produces one new fission. The shape of the reactor core and control rods (that absorb neutrons) combines to serve as a "throttle" to match the energy release to load. The thermal energy produces steam that propels the vessel and provides electric power. All of this technology development was done with private industrial firms under contract by the military and was classified "top secret."

The industrial firms that built the nuclear reactors for the military also built steam turbines and generators for electric power stations. The first nuclear reactor built to produce electric power for domestic consumption was put into service in Shipingsport, Ohio, in 1957, just 15 years after the "Top Secret" Manhattan Project was assembled to build a nuclear weapon. This represents a remarkable technological achievement. Today, modern nuclear reactors produce electricity based on technology similar to that used in the submarines.

In nuclear reactors and the bomb, neutron sources can be used to supplement the neutrons created by the natural decay of U-235 to create greater control in attaining criticality. The chain reaction is started by inserting some beryllium mixed with polonium, radium, or another alpha-emitter. Alpha particles from the decay cause the release of neutrons from the beryllium as it turns to carbon-12.

Reserves

Uranium reserves are difficult to estimate; however, an estimate can be readily made on the energy in the spent rods from U.S. nuclear power generation. Current nuclear technology uses 3.4% of the uranium in the fuel, leaving 96.6% of the uranium unused. The amount of nuclear fuel in spent nuclear fuel rods in U.S. nuclear facilities has an energy content comparable to the entire recoverable U.S. coal reserve.[iii] The depleted uranium created during the fabrication of the initial nuclear fuel rods has about four times as much energy as that remaining in the spent nuclear fuel rods. Combined, this stockpiled uranium in the United States has the capacity to meet all of the U.S. energy needs with near-zero greenhouse gas emissions for the next 250 years.[iv]

Reprocessing Technology

The 250 years of capacity from uranium that has already been mined will require reprocessing. A typical spent nuclear fuel rod in the United States contains about 3.4% fission products, 0.75%–1% unused U-235, 0.9% Pu-239, 94.5% U-238, and trace amounts of atoms having atomic masses greater than U-235 (referred to as transuranic elements).

Not only would reprocessing tap this 250 years of energy available from stockpiled uranium, the additional nuclear waste would be the fission products produced by the recycled uranium fuel.

[iii] Assuming 30 years of spent fuel at the current rate, this translates to 75 years of capacity to meet all U.S. energy needs at the present rate of consumption with near-zero generation of greenhouse gases.

[iv] 250,000 tons of spent fuel were in storage in 2001 worldwide, with waste inventories increasing about 12,000 tons per year. About 3,000 tons of spent fuel are reprocessed in France.

Reprocessing involves removing the 3.4% that is fission products and enriching the U-235 and/or Pu-239 to meet the "specifications" of nuclear reactor fuel. The "specifications" depend on the nuclear reactor design. Nuclear reactors and fuel-handling procedures can be designed that allow nuclear fuel specifications to be met at lower costs than current reprocessing practice in France. For comparative purposes, the cost of coal, U.S. nuclear fuel from mined uranium, and French reprocessed fuel is about 1.05, 0.68, and 0.90¢ per kWh or electricity produced.

From 33% to 40% of the energy produced in nuclear power plants today originates from U-238 and is released by the Pu-239 formed and subsequently fissions: For every three parts of U-235 entering the reactor, about two parts of U-235 plus Pu-239 leave the reactor and, to date, remain stored at the power plant site. All of the uranium, the two parts U-235 and Pu-239 are the target of reprocessing technology. To tap this 250 year stockpile of fuel, new fast-neutron reactors could be put in place that produce more Pu-239 than the combined U-235 and Pu-239 in the original fuel.

Decades of commercial nuclear power provide stockpiles of spent fuel rods, billions of dollars collected on a 0.1 cent per kWh tax levied, and retained to process the spent fuel rods. A remarkable safety history for U.S. designed reactors is set against a costly history of regulations that limit the ability of the technology to advance. These circumstances provide opportunity or perpetual problems, depending on the decisions made to use (or not) nuclear power.

Figure 3-6 summarizes the accumulation of spent fuel currently being stored on site at the nuclear power plants in the United States.

The United States uses about 98 GW of electrical power generating capacity from nuclear energy. The construction and startup of most of these plants occurred between 1973 and 1989. In 2007 the inventory of spent nuclear fuel will correspond to about 30 years of operation at current generation rates of the nuclear power infrastructure. Figure 3-6 approximates the total spent fuel inventories and cumulative inventories of U-235 and Pu-239 under two different scenarios. Figure 3-6 illustrates that reprocessing is the key to decreasing Pu-239 and U-235 inventories and ending the accumulation of spent fuel nuclear reactor sites.

If reprocessing would have initiated in 2005 to meet all current nuclear power plants, the current inventories, along with the Pu-239 that is generated as part of PWR operation, would provide

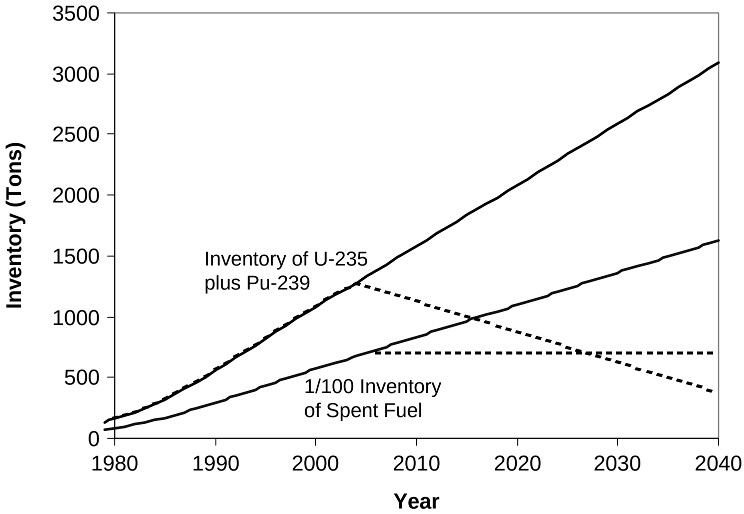


FIGURE 3-6. Approximate inventory of commercial spent nuclear fuel and fissionable isotopes having weapons potential (Pu-239 and U-235). The solid lines are for continued operation without reprocessing, and the dashed lines are for reprocessing (starting in 2005) to meet the needs of current nuclear capacity.

sufficient Pu-239 to operate at existing capacity through 2045. If in 2005 the demand for Pu-239 and U-235 increased threefold (~300 GW capacity), the current inventories would last until 2019. This does not include the use of Pu-239 and U-235 in weapons' inventories, or depend on fast neutron reactor technology to convert the much greater inventories of U-238 into Pu-239 fuel. This partly explains trends of discontinuing breeder reactor research and operation. Breeder reactors will not be needed for some time.

Fast-neutron reactor technology would allow nuclear reactors to meet all energy needs for the next 250 years without generating additional radioactive materials and without mining additional uranium. The potential of this technology should not be ignored.

Geothermal

Geothermal energy is heat that is released from the continuous nuclear decay occurring in uranium that is distributed throughout the Earth. The Earth's core has remained hot for billions of years for two reasons: (1) thousands of feet of the Earth's crust provide a good insulation that hinders the loss of heat to surrounding space; and (2) heavier elements (like uranium) tend to be more concentrated toward Earth's center, where these elements undergo natural radioactive decay releasing heat.

The warmer the geothermal heat source, the more useful the energy. For most locations, higher temperatures are located several thousand feet under the surface, and the cost of accessing them is too great compared to alternatives. At the center of the Earth, some 3,700 miles below the surface, temperatures reach 9,000°F, and metals and rocks are liquid.[25]

At locations such as Yellowstone Park and Iceland, useful geothermal heat is available a few hundred feet under the surface or at the surface (hot springs and geysers). Even at these locations the costs of the underground pipe network necessary to create an electrical power plant is a capital-intensive facility. On a case-by-case basis, geothermal heating has been economical. Much of Iceland's residential and commercial heating is provided by geothermal energy (see box).

Geothermal Heating in Iceland

The first trial wells for hot water were sunk by two pioneers of the natural sciences in Iceland, Eggert Olafsson and Bjarni Palsson, at Thvottalaugar in Reykjavik and in Krisuvik on the southwest peninsula in 1755–1756.[26] Additional wells were sunk at Thvottalaugar in 1928 through 1930 in search of hot water for space heating. They yielded 14 liters per second at a temperature of 87°C, which in November 1930 was piped three kilometers to Austurbacjarskoli, a school in Reykjavik that was the first building to be heated by geothermal water. Soon after, more public buildings in that area of the city as well as about 60 private houses were connected to the geothermal pipeline from Thvottalaugar.

The results of this district heating project were so encouraging that other geothermal fields began to be explored in the vicinity of Reykjavik. Wells were sunk at Reykir and Reykjahbd in Mosfellssveit, by Laugavegur (a main street in Reykjavik), and by Ellidaar, the salmon river flowing at that time outside the city but now well within its eastern limits. Results of this exploration were good. A total of 52 wells in these areas are now producing 2,400 liters per second of water at a temperature of 62–132°C.

Hitaveita Reykjavikur (Reykjavik District Heating) supplies Reykjavik and several neighboring communities with geothermal water. There are about 150,000 inhabitants in that area, living in about 35,000 houses. This is way over half the population of Iceland. Total harnessed power of the utility's geothermal fields, including the Nesjavellir plant, amounts to 660 MWt, and its distribution system carries an annual flow of 55 million cubic meters of water.

Some manufacturers refer to the use of groundwater or pipes buried in the ground used in combination with a heat pump as geothermal furnaces. These furnaces do not use geothermal heat. Rather, the large mass of the Earth simply acts as energy storage to take in heat during the summer and give up heat during the winter.

Recent Solar Energy

Use of Sunlight

Solar energy provides the most cost effective means to reduce heating costs and can be used to directly produce electricity. Both can be cost effective, depending on the local cost of conventional electrical energy alternatives.

Solar heating is the most commonly used and least expensive use of sunlight. Building location, orientation, and window location can be used to displace auxiliary heating such as a natural gas furnace. Windows located on the south side of a northern hemisphere building will bring in sunlight to heat during the winter. A strategically located tree or well-designed roof overhang can block the sunlight during the summer. The number and placement of windows will vary, based on design preference. Aesthetics, solar functionality, and nonsolar functionality (siding on a building) are available for building construction. New building designs are available that provide cost-effective combinations for solar systems.

Solar water heating systems are the next most popular use of solar energy. They use solar heat to reduce the consumption of natural gas or electricity to heat water. Clarence Kemp is known as the father of solar energy in the United States. He patented the first commercial Climax Solar Water Heater.[27] This and competing systems sold about 15,000 units in Florida and California by 1937.

In 1941, between 25,000 and 60,000 were in use in the United States, with 80% of the new homes in Miami having solar hot water heaters. Use outside the United States has developed, especially in regions where electricity costs are high and the climate is warm.

When confronted with the oil boycott and subsequent oil supply incentives, Israel proceeded with a major initiative to use solar water heaters. More than 90% of Israeli households owned solar water heaters at the start of the 21st century.[28] Solar water heaters are also quite popular in Australia. At sunny locations where electricity is expensive and where natural gas is not available, solar water heating is a good option. It is easy to store water so the solar energy collected during the day is available at night.

Considerable research has been conducted using mirrors to focus sunlight and generate the high temperatures required to produce steam for electrical power generation. To date, most of these systems are too costly. Alternatively, the direct conversion of sunlight to electricity is popular in niche markets, and new technology is poised to expand this use.

In the 1950s, Bell Laboratory scientists made the first practical photovoltaic solar cell. Today, photovoltaic technology is widely used on flat screen computer monitors and for producing electrical power for electric devices in remote locations. These remote devices include highway signs that cannot be easily connected to grid electricity and small electrical devices like handheld calculators.

Solar energy is usually not used for power generation in competition with grid electricity. In some locations, photovoltaic cells on roofs provide an alternative for enthusiasts where consumer electrical prices are above $0.10 per kWh. Small solar roof units show a better payback to meet individual electrical needs than commercial units designed to sell power to the electrical grid. While consumers will usually pay more than $0.08 per kWh for electricity, when selling electricity to the grid one typically receives less than $0.04 per kWh.

The south facing walls and roof sections of every building in the United States are potentially useful solar receivers. Materials having both aesthetic and solar function are generally not available today, but such systems will likely be developed. From this perspective, there is great potential for solar energy to replace a portion of grid electrical power. At 0.8 billion kWh in 1999, solar electrical power on the grid provided about 0.02% of the electrical energy production (see Table 3-3).

TABLE 3-3
U.S. electricity power production in 1999 in billions of kilowatt hours.

Coal	1,884.3	50.8%
Nuclear	728.3	19.6%
Natural Gas	556.2	15.0%
Hydroelectric	319.5	8.6%
Petroleum	123.6	3.3%
Wood	37.6	1.0%
MSW	20.2	0.5%
Geothermal	16.8	0.5%
Wind	4.5	0.12%
Solar	0.8	0.02%
Total	3,711.8	

http://www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/oil_market_basics/default.htm. "Electrical Energy Consumption."

Hydroelectric

Water stored in high-elevation lakes or held by dams creates high-pressure water at the bottom of the dam. The energy stored in the high-pressure water can be converted to shaft work using hydroelectric turbines to produce electricity. Most of the good dam sites in the United States have been developed, so this is a relatively mature industry. At 319.5 billion kWh in 1999, hydroelectric power on the grid provided 8.6% of the electrical energy production. Environmentalists oppose dam construction in the Northwest, and there is active lobbying to remove dams on the Columbia River.

Wind Energy

There have been over 8 million wind turbines installed since the 1860s in the United States. Wind energy is one of the oldest and most widely used forms of power. Traditionally, the shaft work was used to pump water or mill grain. In the 1930s, an infant electrical power industry was driven out of business by policies favoring the distribution of fossil fuel electricity.[29]

Between 1976 and 1985, over 5,500 small electric utility units (1–25 kW) were installed on homes and remote locations in response to high oil prices. The installation and use dwindled when government subsidies ended in 1985.[30] More recently, wind farms have been installed to provide grid electrical power. Between 1981 and 1990, approximately 17,000 machines were installed with output ranging from 20 to 350 kilowatts with a total capacity of 1,700 megawatts.[31]

The price of electrical power from wind has decreased from more than $1.00 per kWh in 1978 to about $0.05 per kWh in 1998, with costs projected as low as $0.025 per kWh (for large wind farms). At $0.025 per kWh, wind power competes with the fuel costs for most fossil fuel power plants. Projections aside, for most locations in 2002, a low price for wind power was $0.045 per kWh,[32] but some wind farms need $0.06 per kWh to operate at a profit. The primary issue for more widespread use of wind power is not the cost of the wind turbines. Issues are (1) high maintenance costs because of the large number of wind turbines needed to generate as much power as a typical coal-fired power plant, (2) environmental impact (noise pollution and poor aesthetics), and (3) dependable power on demand. (The wind doesn't always blow.)

The dependability issue is the ability of wind power to supply continuous electrical power. The ability of a facility to provide electricity is characterized by its capacity factor. This factor is the actual energy supplied by a wind turbine compared to the theoretical power supplied if it operated continuously at its design capacity. Wind power suffers from low-capacity factors because of the lack of wind at night and the lack of power demand when the wind is blowing. Capacity factors for wind farms range from 0.20 to 0.35 compared to 0.5 for fossil fuel plants, 0.6 for some new gas turbine plants, and 0.85 for nuclear power.[33]

One of the less obvious opportunities for electrical power supply is energy storage. Storing wind energy as it is available for use during peak demand times will increase the value of the wind energy and would increase capacity factors. This could increase the value of wind energy from a wind farm by a factor of three or more. Such an increase in the value of wind energy would change the economic outlook of wind power from marginal to profitable.

Wind power generated 4.5 billion kWh in 1999 or 0.12% of the electrical energy production in the United States.

Biomass

Energy storage limits the utility for both wind power and solar energy. Nature's way for storing solar energy is biomass. Biomass is biological material: vegetation, grass, wood, corn, palm oil, and similar plant material. Time, the absence of oxygen, and compaction (promoted by Earth overburdens) convert biomass to coal, petroleum, or other geological variations of these materials.

Wood has been used through the ages to produce heat. Today, wood supplies heat and is used to generate electrical power, corn is converted to ethanol, and vegetable oils are converted to biodiesel. Unlike fossil fuels, biomass is not available in reserves that have accumulated for years. Rather, biomass grows each year and must be harvested and used quickly to get quality fuel. The supply must be renewed every year.

The availability of biomass is reported as estimated amounts produced per year. A wide range of biomass types, as well as different terrain and climate, control biomass availability. The supply of biomass tends to increase with increasing prices. Table 3-4 summarizes example prices and availability of solid biomass (not including fats and oils).

Solid biomass is used for energy five different ways: (1) burning for heat or electrical power generation; (2) conversion to ethanol; (3) pyrolysis; (4) gasification; and (5) anaerobic (without oxygen) methane production (landfill gas). The high cost of biomass makes conversion to liquid fuels and use as chemical feed stocks the best applications for most of these renewable energy sources. Direct combustion and anaerobic methane are handled on a case-by-case basis, where they are generally profitable if the biomass has already been collected for other reasons. For quality liquid fuel production, two technologies stand out: ethanol production and gasification for Fischer-Tropsch fuel production. When including oil seed crops (e.g., soybeans and rapeseeds) a third option of biodiesel is also becoming quite attractive.

Ethanol and Biodiesel from Agricultural Commodities

Table 3-4 shows the number of gallons of ethanol that can be produced from the most common forms of biomass. The corn data of Table 3-4 are important points of reference. Corn is the largest commodity crop in the United States and provides high yields of dense biomass. While the price per ton of corn is almost twice the price of large-volume switchgrass and wood, the corn prices and volumes are current, while the other biomass prices are based on estimates that may be optimistic.

Dried distiller grains are a by-product sold as a high-protein, high-fat cattle feed when producing ethanol from corn. Over half

TABLE 3-4
U.S. estimate of supplies and production potential of ethanol from biomass.[A] Except for reliable corn numbers, conversions are optimistic.

	Price $/Dry Ton	*Quantity Million Dry Tons/Yr*	*Conversion Gallons Ethanol / Ton*	*Ethanol Equivalent Millions of Gallons/Yr*	*Cost of Feedstock/ Gallon Ethanol*
$2.40 bu (56 lb) Corn, U.S.[B,C]	85.7	280	89	24,920	$0.96
Refuse Derived Waste	15	80	80	6,400	$0.19
Wood Waste *Cheap*	30	10	110	1,100	$0.27
Wood Waste *Expensive*	45	80	110	8,800	$0.41
Switchgrass *Cheap*	25	5	95	475	$0.26
Switchgrass *Expensive*	45	250	95	23,750	$0.47

Estimated per-ton yields of ethanol from corn, sorghum, refuse-derived fuel, wood waste, and stitchgrass are 89, 86, 80, 110, and 95, respectively. Corn has 56 pounds per bushel with an assumed price of $2.40 per bushel ($85.71/ton) with an annual U.S. production estimate of 10 billion bushels or 280 million tons.

[A] K. Shaine, T. S. Tyson, P. Bergeron, and V. Putsche, "Modeling the Penetration of the Biomass-Ethanol Industry and Its Future Benefits," September 18, 1996, Bioenergy '96, Opryland Hotel, Nashville, TN.

[B] R. M. Tshiteya, *Conversion Technologies: Biomass to Ethanol*. Golden, CO: National Renewable Energy Laboratory, September 1992, pp. 3–5.

[C] http://www.usda.gov/nass/pubs/trackrec/track02a.htm#corn. Corn production U.S.

of the corn costs are recovered by the sale of this by-product.[34] It is because of these by-products that corn is used more than other biomass crops (e.g., sugar cane). Other biomass materials may actually have a higher yield of ethanol per acre, but they do not have the valuable by-products.

Corn is the most commonly used biomass for producing ethanol. The production process consists of adding yeast, enzymes, and nutrients to the ground starchy part of corn to produce a beer. The beer contains from 4% to 18% ethanol, which is concentrated by distillation that is similar to the distillation used to produce whiskey. The final fuel ethanol must contain very little water for use as motor fuel. In gasoline, the water is an insoluble phase that extracts the ethanol and settles to the bottom of the tank. If this water gets to the engine, the engine will stall.

About 90 gallons of ethanol are produced from one ton of corn. The production cost is \$1.05 to \$1.25 per gallon. Ethanol has about two-thirds the energy content of gasoline,[35] so these prices translate to \$1.57 to \$1.85 per equivalent gasoline gallon. This is more than gasoline that is produced for about \$1.30 per gallon[v] before the \$0.42 (average) motor fuel tax is added.

Estimates of gasoline used in U.S. cars, vans, pickup trucks, and SUVs are about 130 billion gallons of gasoline per year.[36] (These numbers agree with the motor gasoline consumption of 3.05 billion barrels reported elsewhere.) About 500 million prime, corn-producing acres would be required for ethanol to replace all of the gasoline. This is about one-quarter of the land in the lower 48 states. The lower 48 states have about 590 million acres of grassland, 650 million acres of forest, and 460 million acres of croplands (most is not prime acreage).[37]

If all of the current corn crop were converted to ethanol, this would replace about 17 billion gallons of gasoline—less than 15% of our current consumption. Estimates of dedicating acreage for ethanol production equivalent (yield-based) to current gasoline consumption would require nine times the acreage used for the current U.S. corn crop. This approach is not realistic. However, if hybrid vehicle technology doubles fuel economy and the electrical power grid further reduces gasoline consumption to about 60 billion gallons, substantial ethanol replacement of gasoline is possible. Use of perennial crops would be a necessary component of large-volume ethanol replacement for gasoline.

Corn is an annual crop and must be planted each year. For this reason, costs for mass production of wood and grasses are potentially less than corn. In the late 20th century, corn-to-ethanol production facilities dominated the biomass-to-ethanol industry. This was due to (1) less expensive conversion technologies for starch-to-ethanol compared to cellulose-to-ethanol required for wood or grasses and (2) generally ambitious farmer-investors who viewed this technology as stabilizing their core farming business and providing a return on the ethanol production plant investment. State governments usually provide tax credits for investment dollars to build the ethanol plants, and there is a federal subsidy for fuel grade ethanol from biomass.

[v] \$50 per barrel divided by 42 gallons per barrel plus a refining cost.

Because of lower feedstock costs (see Table 3-4), wood-to-ethanol and grass-to-ethanol technologies could provide lower ethanol costs—projections are as low as $0.90 per equivalent gasoline gallon.[38] Research focus has recently been placed on cellulose-to-ethanol. The cost of cellulose-to-ethanol has improved from more costly to about the same as corn-to-ethanol technology. Based on present trends, cellulose-to-ethanol technology could dominate ethanol expansion in the 21st century. It would require large tracts of land dedicated to cellulose production.

The current world production of oils and fats is about 240 billion pounds per year[39] (32.8 billion gallons, 0.78 billion barrels), with production capacity doubling about every 14 years. This compares to a total U.S. consumption of crude oil of 7.1 billion barrels per year[40] of which 1.35 billion barrels is distillate fuel oil (data for the year 2000).[41] With proper quality control, biodiesel can be used in place of fuel oil (including diesel) with little or no equipment modification. Untapped, large regions of Australia, Colombia, and Indonesia could produce more palm oil. This can be converted to biodiesel that has 92% of the energy per gallon as diesel fuel from petroleum.[42] This biodiesel can be used in the diesel engine fleet without costly engine modifications.

In the United States, ethanol is the predominant fuel produced from farm commodities (mostly from corn and sorghum), while in Europe, biodiesel is the predominant fuel produced from farm commodities (mostly from rapeseed). In the United States, biodiesel is produced predominantly from waste grease (mostly from restaurants and rendering facilities) and from soybeans.

In the United States, approximately 30% of crop area is planted to corn, 28% to soybeans, and 23% to wheat.[43] For soybeans this translates to about 73 million acres (29.55 million hectares) or about 2.8 billion bushels (76.2 million metric tons). Soybeans are 18%–20% oil by weight, and if all of the U.S. soybean oil production were converted[vi] to biodiesel, it would yield about 4.25 billion gallons of biodiesel per year. Typical high yields of soybeans are about 40 bushels per acre (2.7 tons per hectare), which translates to about 61 gallons per acre. By comparison, 200 bushels per acre of corn can be converted to 520 gallons of ethanol per acre.

Table 3-5 compares the consumption of gasoline and diesel to the potential to produce ethanol and biodiesel from U.S. corn

[vi] 76.2 million metric tons of beans is about 14.5 billion kilograms of soybean oil. This translates to about 16 billion liters, using a density of 0.9 g/cc or about 4.25 billion gallons per year.

TABLE 3-5
Comparison of annual U.S. gasoline and diesel consumption versus ethanol and biodiesel production capabilities.

Gasoline Consumption (billions of gallons per year)	130
Distillate Fuel Oil (including diesel) Consumption	57
Ethanol from Corn (equivalent gasoline gallons)	25 [17]
Biodiesel from Soybeans (equivalent diesel gallons)	4.25 [3.8]

and soybeans. If all the starch in corn and all the oil in soybeans were converted to fuel, it would only displace the energy contained in 21 billion gallons of the 187 billion gallons of gasoline and diesel consumed in the United States. Thus, the combined soybean and corn production consumes 58% of the U.S. crop area planted each year. It is clear that farm commodities alone cannot displace petroleum oil for transportations fuels. At best, ethanol and biodiesel production is only part of the solution. U.S. biodiesel production in 2005 was about 0.03 billion gallons per year compared to distillate fuel oil consumption of 57 billion gallons per year.

Converting corn and soybean oil to fuel is advantageous because the huge fuel market can absorb all excess crops and stabilize the price at a higher level. In addition, in times of crop failure, the corn and soybeans that normally would be used by the fuel market could be diverted to the feed market. The benefits of using soybeans in the fuel market can be further advanced by plant science technology to develop high-oil content soybeans.

Soybeans sell for about $0.125 per pound, while soybean oil typically sells for about twice that ($0.25 per lb). The meal sells for slightly less than the bean at about $0.11 per pound. Genetic engineering that would double the oil content of soybeans (e.g., 36%–40%) would make the bean, on the average, more valuable. In addition, the corresponding 25% reduction in the meal content would reduce the supply of the meal and increase the value of the meal. At a density of 0.879 g/cc, there are about 7.35 lbs of biodiesel per gallon. A price of $0.25 per lb corresponds to $1.84 per gallon; $0.125 per lb to $0.92 per gallon.

Fuel production from corn and soybean oil would preferably be sustainable without agricultural subsidies of any kind (none for ethanol use, biodiesel use, farming, or not farming). A strategy thus emerges that can increase the value of farm commodities, decrease oil imports, decrease the value of oil imports, and put U.S. agriculture on a path of sustainability without government subsidies. To be successful, this strategy would need the following components:

1. **Develop better oil-producing crops**.
   - Promote genetic engineering of soybeans to double oil content and reduce saturated fat content (saturated fats cause biodiesel to plug fuel filters at moderate temperatures).
   - Promote the establishment of energy crops like the Chinese tallow tree in the South that can produce eight times as much vegetable oil per acre as soybeans.
2. **Pave the future for more widespread use of diesel engines and fuel cells**.
   - Promote plug-in HEV technology[44] that uses electricity and higher fuel efficiency to displace 80% of gasoline consumption. Apply direct-use ethanol fuel cells for much of the remaining automobile transportation energy needs.
   - Continue to improve diesel engines and use of biodiesel and ethanol in diesel engines. Fuel cells will not be able to compete with diesel engines in trucking and farm applications for at least a couple decades.
3. **Pass antitrust laws that are enforced at the border**.
   - If the oil-exporting countries allow the price of petroleum to exceed $70 per barrel ($2.00 per gallon diesel, not including highway taxes), do not allow subsequent price decreases to bankrupt new alternative fuel facilities.
4. **Fix the dysfunctional U.S. tax structure**.
   - Restructure federal and state taxes to substantially eliminate personal and corporate income taxes and replace the tax revenue with consumption taxes (e.g., 50%) on imports and domestic products. This would increase the price of diesel to $2.25 per gallon (red diesel, no highway tax).
   - Treat farm use of ethanol and biodiesel as an internal use of a farm product, and, therefore, no consumption tax would be applied.

Increased use of oil crops would include use of rapeseed in drier northern climates (rapeseed contains about 35% oil) and use of Chinese tallow trees in the South. Chinese tallow trees are capable of producing eight times as much oil per acre as soybeans. If Chinese tallow trees were planted in an acreage half that of soybeans and the oil content of soybeans were doubled, 17–20 billion gallons of diesel could be replaced by biodiesel allowing continued use of soybean oil in food applications. This volume of biodiesel production would cover all agricultural applications and allow the imports to be optional.

Chinese tallow trees are one of the fastest-growing trees. In addition to producing oil crops, clippings and old trees could be used for ethanol production. Chinese tallow tree orchards could readily become the largest agriculture crop in the United States. High-protein animal feed is an additional potential by-product.

The plug-in HEV technology would displace about 104 billion gallons per year of gasoline with electricity and increase efficiency. The electricity could be made available from the reprocessed spent nuclear fuel and adding advanced technology nuclear reactors. About half of the remaining 26 billion gallons of gasoline could be displaced with ethanol and half with continued use of gasoline.

In this strategy, up to 55 billion gallons of annual diesel and gasoline consumption would still need to be met with fossil fuel sources. These could be met with petroleum, coal-derived liquid fuels (like Fischer-Tropsch fuels), and Canadian oil sand fuels. Increase of electric trains for freight could displace much of the 55 billion gallons. It would be a buyer's market for liquid fossil fuels.

These proposed technologies are cost effective and sustainable at $55 per barrel of crude oil and a tax strategy that equally taxes domestic and imported products (the consumption tax). A variety of continued strategies would assure that the United States did not have to import petroleum and that farmers could achieve higher-value nonfood uses for their products.

The consumption tax is emerging as a preferred way to end the stress on U.S. manufacturing with domestic taxes that are not applied to imports. Oil prices are already $55 per barrel level. All the technology to replace petroleum is demonstrated and cost-effective with the possible exception of low-temperature direct-use ethanol fuel cells. Intermediate temperature PEM fuel cells should make direct use of ethanol cost effective in ten years.

Table 3-6 summarizes the current uses, volumes, and prices of ethanol production and compares these to a likely scenario if a consumption tax is implemented and antitrust laws are enforced at the border. Table 3-7 summarizes the impact of the current federal incentive of 5.4¢ per gallon tax exemption that goes to blenders placing 10% ethanol in gasoline—this is applied against the 18.4¢ federal excise tax on gasoline.[45] The federal tax incentive is paid to the blenders, so if the blender pays $1.25 per gallon for ethanol, the federal government provides a reduction ($0.54 per gallon of ethanol blended to 10% ethanol in gasoline) in the highway taxes that are paid by the blender.

TABLE 3-6
Current and projected costs and production of U.S. ethanol and biodiesel.

	Application	*Billions of Gallons per Year*	*Pricing*
2005			
Ethanol[liv]	Octane Enhancer, Oxygenate for CO Nonattainment	3.4	\$1.20–\$1.50
Biodiesel	Primarily as 2% to 20% Additive in Bus Fleets and Farm Applications	0.03	\$1.30–\$2.30 per gallon
2015 (2025)			
Ethanol	Direct-Use Ethanol Fuel Cells, Octane Enhancer, Oxygenate for CO Nonattainment Areas	10 (20)	\$1.50 per gallon
Biodiesel	Predominant Farm Fuel, 50% Market Share in South, Fleets	5 (15)	\$2.10 for farm application (soybean and rapeseed based, no tax); \$2.25 for South (beef tallow tree based, including consumption tax)

[liv]2004 Gasoline Price Increases: An Analysis Summary Prepared by Renewable Fuels Association. (http://www.ethanolrfa.org/, March 2004.)

TABLE 3-7
Example cost of ethanol and impact of tax credit.

Example Ethanol Wholesale Price	123¢/gallon
Alcohol Fuel Tax Incentive	54¢/gallon
Effective Ethanol Price	69¢/gallon
Effective Ethanol Price for Energy in 1 Gallon Gasoline	103¢
Gasoline Wholesale Price (\$55/barrel crude oil, \$0.14/gallon refining cost)	145¢/gallon

The price of petroleum fuels relative to the price of vegetable oil is an important factor that will impact sustainable biodiesel and ethanol production. Based on $55 per barrel petroleum and a consumption tax strategy that would tax imports the same as domestic production, there is a basis for developing a biodiesel and ethanol industry that can be sustainable and compete with $2.25 per gallon diesel (includes consumption tax, excludes highway tax).

The price of vegetable oil ranges from $0.92 to $1.84, depending on whether the oil is priced at the same value as the soybean or a premium price is received for the oil component of the bean. In principal, higher-oil seed crops could sustainably provide vegetable oil at $1.50 per gallon while maintaining a premium value (more on a per-pound basis than soybeans) for the bean. At a reasonable $0.40 per pound processing cost, a biodiesel cost of $1.90 per gallon would be sustainable. Prices as low as $1.70 per gallon may be attainable with catalyst development. This gives $2.25 per gallon for diesel. With the 50% consumption tax, imported oil would have to be below $45 per barrel for the price of the diesel to be less than $1.90 per gallon.

Current subsidies of $0.54 per gallon for ethanol and $1.00 per gallon for biodiesel approximately compensate for all the U.S. taxes collected on agriculture and processing that go toward the production of these fuels (essentially no U.S. taxes are applied on imported petroleum). These incentives are appropriate in view of current U.S. tax strategies. A continued use of these incentives rather than a consumption tax would have at least three drawbacks: (1) many citizens will perceive the incentive as political favor rather than a mechanism to allow the fuels to compete fairly with imported petroleum, (2) the incentives require periodic renewal and can be eliminated when production becomes high enough, and (3) the incentives currently do not apply to other technologies such as plug-in HEV technology that would help realize the true value of ethanol to replace petroleum.

If large-scale Chinese tallow tree farming were to occur, the farming should be profitable at oil prices as low as $1.30 per gallon ($0.90 per gallon for the oil plus $0.40 for processing). At these prices, the biodiesel would compete in the trucking fuel industry where a 50% consumption tax would take that to $1.95 per gallon—considerably less than petroleum at $2.25 per gallon.

For ethanol use in advanced plug-in HEVs, the technology is demonstrated and cost effective with the possible exception of low-temperature direct-use ethanol fuel cells. Intermediate temperature PEM fuel cells should make direct use of ethanol cost effective in less than ten years.

Consumption taxes will not represent an additional tax burden on U.S. consumers if properly implemented; however, the taxes will be more apparent. The average consumer will undoubtedly welcome the absence of income taxes. However, when the price tag on that new $30,000 pickup truck becomes $45,000, there will be some distress. The implementation should be gradual to allow consumers to become accustomed to paying taxes, at the point of sale rather than on income. An initial phase of eliminating corporate income taxes, about a 5% reduction in all personal income taxes and a 20%–30% consumption tax, would be a good start. The price of a pickup truck should not increase by 20%–30%, because the lack of corporate income taxes, should allow the $30,000 pickup to first have a price decrease to about $28,000 and a total price of about $34,000 when the tax is applied.

The United States is poised to level the playing field between imported and domestic production through use of consumption taxes. This correction to a current tax structure is much needed. If and when this transition happens, U.S. farmers would do well to support the transition and to make sure that ethanol and biodiesel used in agricultural applications would be free of this consumption tax. It should be considered an internal transaction.

Emergence of Nuclear Power

In the pursuit of sustainable energy, nuclear power emerges for four reasons:

1. On a Btu basis, nuclear fuel is the least expensive, and it is economically sustainable. Nuclear fuel has the potential to be ten times less expensive than any alternative (less than $0.10 per MBtu).
2. Nuclear fuel is the most readily available fuel. It is stockpiled at commercial reactors in the form of spent fuel.
3. Nuclear fuel is the most abundant. Enough has already been mined, processed, and stored in the United States to supply all energy needs for centuries.
4. There is no technically available alternative to give sustainable energy supply for current and projected energy demand.

This last point is emphasized in this chapter. It is impractical to try to replace transportation fuels with biomass, let alone nontransportation energy expenditures. The limited availability of petroleum is already inciting military conflict to keep the oil flowing, not to mention the contribution of the trade deficit drag on the U.S. economy. The imports of natural gas are growing rapidly, and at prices greater than $6 per MBtu, it is too expensive for use for electrical power generation.

Coal will be important for decades to produce electrical power and for centuries as a feedstock to the chemical industry. However, coal is already used for about 50% of electric power production (see Table 3-3). Nuclear energy is less expensive on a fuel basis. Chapter 13 provides a more rigorous comparison of electrical power costs for coal versus nuclear.

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