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INTRODUCTION TO ENERGY SYSTEMS

Webster's dictionary defines energy as "capacity for action or performing work." Both potential energy stored in a body held in a force field (say the gravitational field at an elevation) and kinetic energy of a moving body are forms of energy from which useful work may be extracted. Energy associated with the chemical bonds that hold atoms and molecules together is potential energy. In the case of fuel combustion, this form of energy is transformed primarily into kinetic energy of the molecules as vibrational, rotational, and translational and referred to as thermal energy, by exothermic combustion reactions, and may be transferred as heat and a portion of it may be converted into work utilizing a heat engine. The first and the second laws of thermodynamics govern these energy transformation processes. The first law, a law of experience, recognizes energy conservation in nature while the second law, also a law of experience, recognizes that the overall quality of energy cannot be increased. In fact, for real processes, the overall quality of energy decreases due to the requirement for a reasonable potential difference to drive the energy conversion process at finite (nonzero) rates (e.g., heat or mass transfer with finite driving forces, temperature in the case of heat, and chemical potential in the case of mass) resulting in inefficiencies (or irreversibilities) such as friction.

Thus, in summary, any action occurring in nature is accompanied by a reduction in the overall quality of energy (a consequence of the second law) while energy is neither destroyed nor created (a consequence of the first law), but transformed into state(s) or form(s) with an overall lower quality or potential (again a consequence of the second

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law). Per Einstein's famous equation, $E = mc^2$ relating mass m and energy E (c is the speed of light), matter should also be included in the energy conservation principle stated earlier when involving nuclear energy.

Natural or human processes harness higher forms of energy, convert a fraction of it to useful form (the upper limit of this fraction being constrained by the second law), and ultimately all the energy is downgraded to lower forms of energy and rendered often useless. Thus, there is a continuous depletion of useful energy forms and the rate of depletion depends on how close the fraction of energy converted to useful forms approaches the limit set by the second law; in other words, the energy resource depletion rate depends on how efficient the conversion processes are. The pollutants generation rate is also increased in proportion to energy resource usage rate with a given set of technologies. Thus, it is imperative that higher efficiency processes, that is, processes that convert a higher fraction of energy supplied into useful forms, be pursued for the sustainability of our planet, that is, for the conservation of resources as well as reduction of the environmental impact.

1.1 ENERGY SOURCES AND DISTRIBUTION OF RESOURCES

Fossil fuels such as natural gas, petroleum, and coal are the primary sources of energy at the current time while oil shale resources (not to be confused with shale gas or oil) are being exploited only to a limited extent at the present time (primarily in Estonia) due to the relatively higher costs. Nuclear by fission of radioactive elements has been used to a lesser extent in most countries than fossil fuels except in France where the majority of electricity is produced in nuclear power plants. Renewables include biomass, geothermal, wind for turning turbines to generate electricity, solar used directly to supply heat or in photovoltaic cells, and rivers that provide hydroelectricity, which in certain regions such as the U.S. Pacific Northwest and in Norway and Sweden is quite significant. It should be appreciated that it is the solar energy that actually "drives" wind as well as the rivers by evaporating water and transporting it back as clouds to form rain at the higher elevations.

1.1.1 Fossil Fuels

According to the biogenic theory, fossil fuels are remains ("fossils") of life forms such as marine organisms and plant life that flourished on our planet millions of years ago. This energy is thus a stored form of solar energy that accumulated over millions of years. At the current and projected rates of usage however, it is unfortunate that fossil fuels will be used up in a fraction of time compared to the time it took to collect the energy from the sun. Ramifications include losing valuable resources for synthesizing chemicals as well as shocking the environment by pumping the very large quantities of CO_2 into the atmosphere at rates much higher than the rates at which the CO_2 can be fixed by life forms on our planet. Buildup of CO_2 in the atmosphere results in global warming, the sun's radiation falling on earth's surface that is reradiated as infrared heat is intercepted by the CO_2 (and other greenhouse gases such as CH_4) present in the earth's atmosphere resulting in energy accumulation, the increase in earth's temperature dependent on the concentration of such gases.

Among the various fossil fuels, treated natural gas as supplied which is mainly CH_4 is the cleanest. The naturally occurring sulfur compounds are removed (a small amount of odorant consisting of a sulfur bearing organic compound such as a mercaptan is however added for safety since a leak can be detected from the odor), while there is no ash present in this gaseous fuel. Only minor amounts of other elements or compounds are present. With a hydrogen to carbon (H/C) ratio being highest among all fossil fuels and the fact that natural gas can be utilized for generating power at a significantly higher overall plant efficiency (a measure of the fraction of the energy contained in the fuel converted into net electrical energy output by the plant), the greenhouse gas CO_2 emission can be lowest among the various fossil fuels.

The United States with its vast coal reserves can meet its energy demands for the next 300 years, but coal is the dirtiest fossil fuel since it contains sulfur and nitrogen that form their respective oxides during combustion and known pollutants, ash that can also cause environmental damage, and has low H/C ratio, which means high CO_2 emissions.

Natural gas is simplest in terms of composition and being a gas mixes readily in the combustor and burns relatively cleanly. Furthermore, pollution abatement measures are more easily implemented in natural gas-fueled plants. On the other hand, coal which has a very complex structure containing various elements in addition to carbon and hydrogen and being a solid is more difficult to burn cleanly. Coal combustion undergoes a complex process of drying/devolatilization followed by oxidation of the released gases and the char formed, while a significant fraction of the ash forms particles typically 10 μm or less in size called fly ash. The low visibility around some of the older coal-fired power plants that are not equipped with particulate removal systems from the flue gas or removal systems that are not very efficient is due to the fly ash.

Liquid fuels derived from petroleum are intermediate between natural gas and coal with respect to the environmental signature. From a combustion efficiency standpoint that also relates to minimizing formation and emission of unwanted pollutants, oil being a liquid needs to be atomized typically to less than 10 μm within the combustor to provide a large surface area so that it can vaporize and mix before combustion can occur. Combustion of oil can produce soot particles as well as other pollutants such as unburned hydrocarbons depending on how well the combustion process is designed. Ash particles may also be emitted depending on the type of oil being burnt.

The overall efficiency for a fuel-based power plant is expressed by the ratio of the net power produced by the plant and the "heating value" of the fuel (as a measure of the energy supplied by the fuel). There are two types of heating values used in industry, the higher heating value (HHV) and the lower heating value (LHV). The HHV is obtained by measuring the heat released by combustion of a unit amount of fuel with air at an initial defined standard temperature[1] and cooling the combustion

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[1] 25°C per the American Petroleum Institute while 60°F per the Gas Processors Suppliers Association.

products to that initial temperature while condensing the H_2O vapor formed (and adding the released latent heat of condensation). It may also be calculated from the heat of formation data as explained in Chapter 2. Empirical correlations have been developed for fuels such as coal where the heat of formation data is not available. The Dulong–Petit formula is sometimes used in estimating the HHV of coal when experimental data is not available. It is also used for estimating the HHV of other fuels such as biomass again when experimental data is not available but with limited success. Other correlations have been developed and a summary of various such formulae are presented by García et al. (2014).

The LHV as defined in North America consists of not taking credit for the heat of condensation of the H_2O formed by combustion, that is, LHV = HHV − Latent heat of water vapor formed. In Europe, the International Energy Agency's definition of LHV for fuels such as coal is used instead, which is calculated from the HHV as follows: $\text{LHV} = \text{HHV} - 212 \times \text{H} - 24 \times \text{H}_2\text{O} - 0.8 \times \text{O}$, where H and O are the weight percentages of hydrogen and oxygen in the fuel on an "as-received" (i.e., in the condition received at the plant, which includes its moisture and ash contents) basis, H_2O is the weight percentage of moisture in the as received fuel, and both HHV and LHV are in kilojoule per kilogram of coal on an as received basis. This definition results in a value for the LHV that is typically lower than that as defined in North America, making the LHV-based efficiency reported by European authors higher. Thus, this difference in the definition of LHV should be taken into account while comparing the efficiency of energy conversion systems as reported by European and North American authors, in addition to whether the efficiency is on an LHV or HHV basis. Typically, the LHV efficiency is used for reporting the overall plant efficiency of gas-fired power systems, while in the United States, the HHV efficiency is used for solid fuel (e.g., coal and biomass) fired power systems.

Since the difference between HHV and LHV of a fuel depends on its hydrogen content, the ratio of LHV to HHV is lowest for H_2 at 0.846, highest for CO at 1.00, while for CH_4 it is 0.901. For a liquid fuel such as diesel, this ratio is about 0.93–0.94 while that for ethanol is 0.906. For a bituminous coal such as the Illinois No. 6 coal, this ratio is around 0.968; for a subbituminous coal from the Powder River Basin, Wyoming, this ratio is around 0.964; and for a lignite from North Dakota, this ratio is around 0.962. Since the difference between the HHV and the LHV is significant for most fuels, it is important to specify whether the efficiency reported is on an HHV or LHV basis.

The characteristics of these fossil fuel resources are discussed next in more detail including brief descriptions of the initial processing required before these resources can be utilized for energy recovery. This front-end processing requirement should be taken into account to get a complete picture of the environmental impacts of these resources, that is, from a "cradle to grave" standpoint, which in the case of transportation fuels is referred to as "well to wheel" or "mine to wheel."

1.1.1.1 Natural Gas Natural gas like petroleum is believed to be derived from deposits of remains of plants and animals (probably microorganisms) from millions of years ago according to the biogenic theory. Natural gas may be found along with petroleum or by itself as in many gas fields where little or no oil is found. According to another theory called the abiogenic theory however, natural gas was produced from nonliving matter citing the presence of CH_4 on some of the other planets and moons in our solar system.

Along with CH_4 that is by far the major combustible constituent of natural gas, other light hydrocarbons present in natural gas include C_2H_6, C_3H_8, and C_4H_{10}. Raw natural gas may contain CO_2 and sometimes N_2 and these gases have no heating value. CO_2 is typically removed from the natural gas while C_2H_6, C_3H_8, and C_4H_{10} are usually removed and marketed separately as special fuels or as feedstocks for the manufacture of petrochemicals. A number of other elements and compounds are also found in natural gas such as H_2, H_2S, and He. H_2S is also removed from the natural gas before it is pipelined for sale. H_2S is a toxic gas and its oxides formed during combustion of the fuel are pollutants as discussed later in this chapter. Table 1.1 (Rao et al., 1993) shows typical contract specifications for natural gas.

The composition of natural gas can vary significantly as shown by the data presented in Table 1.2 (Rao et al., 1993), however. Variability in composition of the natural gas can also occur during peak demand months in certain areas of the United States (the northeast). During such periods, natural gas may contain as much as 4% by volume O_2. The gas supply company may blend in propane or butane to extend the fuel supply during such peak demand and air is added as a diluent to hold the Wobbe Index (a measure of the relative amount of energy entering the combustor for a fixed pressure drop across a nozzle and discussed in more detail in Chapter 6) within limits.

Recent discoveries of "unconventional natural gas" have increased the supply of this fossil fuel, especially in the United States, while the potential for a smaller carbon footprint when compared to other fossil fuels has created a renewed interest in its use.

TABLE 1.1 Typical U.S. contract specifications for natural gas

Specification	Limits for custody transfer[a]
H_2S	0.25–1.0 grains/100 standard ft^3
Mercaptans (odorants)	1.0–10.0 grains/100 standard ft^3
Total sulfur	10–20 grains/100 standard ft^3
CO_2	2% by volume
O_2	0.2% by volume
N_2	3% by volume
Total inert gases	4% by volume
H_2	400 parts per million by volume (ppmv)
CO	None
Halogens	None
Unsaturated hydrocarbons	None
Water	7 lbs/10^6 standard ft^3 (118 kg/10^6 normal m^3)
Hydrocarbon dewpoint	45°F at 400 psig (7.2°C at 27.6 barg)
HHV	975 Btu/standard ft^3, minimum (38.4 MJ/normal m^3)

[a] 15.43 grains = g; 100 standard ft^3 (at 60°F, 1 atm) = 2.679 normal m^3 (at 0°C, 1 atm).

TABLE 1.2 Variation in composition of natural gas

	Volume (%)			
Component	Mean	Standard deviation	Minimum	Maximum
CH_4	93.0	5.5	73	99
C_2H_6	3.0	2.6	0	13
C_3H_8	1.0	1.4	0	8
C_4H_{10}	0.5	1.0	0	7
C_5H_{12}	0.1	0.3	0	3
C_6H_{14}	0.1	0.1	0	1
N_2	1.5	2.9	0	17
CO_2	0.5	0.5	0	2

For a 100-year time horizon with mean fugitive emissions of CH_4 as estimated by Howarth et al. (2011), a state-of-the-art coal-fired power plant that is described in Chapter 8 (assuming a bituminous coal) requires approximately 40% carbon capture and sequestration for similar greenhouse gas emissions per net MW as a state-of-the-art shale derived natural gas fired gas turbine-based combined cycle power plant that is described in Chapter 9. In such combined cycles, exhaust heat from the gas turbine (Brayton cycle) is utilized for generating steam that is then used in a steam turbine (Rankine cycle) to generate additional power. Compounding the challenge of CO_2 capture and sequestration from a coal-fired power plant is the associated decrease in the overall plant efficiency that further increases the amount of the required CO_2 capture amount for similar greenhouse gas emissions on a net MW basis for the two types of fuels. Existing coal-fired boiler plants may be converted to natural gas-fired combined cycles while utilizing a significant portion of the existing equipment.

Natural gas-fired combined cycles with their lower capital cost as compared to coal-based power can complement renewables such as solar and wind that are intermittent in nature. Other advantages include their suitability to small-scale applications such as distributed power generation where the power plant is located close to the load and does not depend on the conventional mega scale electric supply grid, and for combined heat and power (CHP) that is discussed in Chapter 10.

Unconventional natural gas consists of (i) “tight gas” that is contained in low permeability reservoirs, (ii) coal bed methane that is adsorbed in coal, and (iii) shale-associated gas that is contained in low permeability shale formations (whose permeability is even lower than that of tight gas reservoirs) and whose supply is rapidly rising. Conventional reservoirs of natural gas are contained in porous rock formations of sandstone and carbonates such as limestone and dolomite, and contain gas in interconnected pore spaces through which the gas can flow ultimately to the wellbore. In the case of coal bed methane, the gas is recovered from coal seams by usually releasing pressure. CO_2 injection to displace the adsorbed natural gas is also being considered. Recovery of tight gas as well as shale-associated gas typically requires stimulation of the reservoir to create additional permeability. Directional drilling in the horizontal direction exposes a much larger portion of the reservoir than conventional vertical wells making it cheaper on a well to well basis and is thus more conducive to developing tight and shale gas resources (see Fig. 1.1). Horizontal drilling consists of drilling down to say 600 m, then horizontally for approximately 1½ km by which the well runs along the formation, opening up more opportunities for gas to enter the wellbore. Permeability is increased by hydraulic fracturing after the well has been drilled and completed. It involves breaking apart (shale) rocks in the formation by pumping large quantities of liquid (~20,000 m^3 of water with 9.5% proppant particles such as sand and 0.5–1% chemicals additives) into the well under high pressure to break up the rocks in the reservoir. The proppant particles keep an induced hydraulic fracture open after the fracking liquid pressure is released. The gas is recovered as pressure is released. Some 750 chemical compounds are added to the water that include lubricants, biocides to prevent bacterial growth, scale inhibitors to prevent mineral precipitation, and corrosion inhibitors and clay stabilizers to prevent swelling of expandable clay minerals.

The U.S. Energy Information Administration's (2013a) estimates of technically recoverable shale gas in 2012 were the highest for China at 32×10^{12} m^3 followed by the United States at 20×10^{12} m^3, while 207×10^{12} m^3 on a worldwide basis, which is a significant fraction of the total worldwide natural gas reserve, about one-third of the total. To put these numbers in perspective, the annual consumption of the gas in the year 2012 was 3.4×10^{12} m^3 on a worldwide basis.

Shale gas typically has significantly more higher hydrocarbon (higher than CH_4) content than conventional natural gas that helps improve the overall economics since these higher hydrocarbons can be recovered and sold separately at a higher value.

In addition to the higher hydrocarbons, natural gas at the well head typically contains acid or "sour" gases such as CO_2 and H_2S as mentioned previously, moisture,

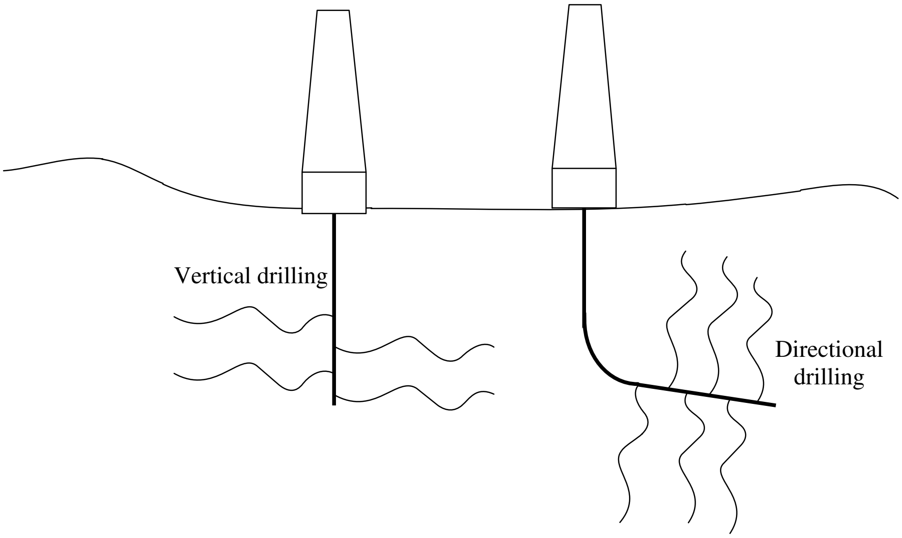

FIGURE 1.1 Vertical versus directional (essentially horizontal) drilling

and range of other unwanted components that must be removed. Treatment involves a combination of adsorptive, absorptive, and cryogenic steps. The sour gases form corrosive acids when combined with H_2O, for example, CO_2 forms carbonic acid. Additionally, CO_2 decreases the heating value of the natural gas. In fact, natural gas is not marketable when the concentration of CO_2 is in excess of 2–3%. H_2S in addition to being an extremely toxic gas is very corrosive in the presence of moisture. Sour gases may be separated from the natural gas by contacting with monoethanolamine (MEA) in a low pressure operation when requiring stringent outlet gas specifications. Diethanolamine (DEA) is used in medium to high pressure treating. DEA does not require solvent reclaiming as does MEA where unwanted stable compounds are formed from the natural gas contaminants. Hg may also be present in natural gas in which case the treatment process includes adsorption. It is preferred to use a regenerative process so that the generation of a hazardous stream consisting of the Hg laden adsorbent is avoided. These types of mass transfer processes are described in Chapter 5.

Another component that may be present in natural gas is He and finds industrial uses. It is cryogenically separated and recovered when its concentration is greater than 0.4% by volume in the natural gas. It may be further purified in a pressure swing adsorption (PSA) process. Both distillation and PSA are described in Chapter 5. The higher hydrocarbons: C_2H_6, C_3H_8, and C_4H_{10} represent added value over regular pipeline gas while the "condensate" consisting of C_5+ fraction can be used as gasoline. Also, condensate removal is often required to meet dew point specifications of pipeline gas, that is, to avoid condensation within the pipeline.

Example 1.1. Assuming ideal gas behavior, calculate the LHV and the HHV of natural gas in kilojoule per standard[2] cubic meter (kJ/Sm^3) corresponding to the "mean" composition shown in Table 1.2 utilizing LHV and HHV data provided for each of the components in Table 1.3. Assume that the C_4 through C_6 hydrocarbons are all straight chained (i.e., they are "normal" designated by an "*n*" hydrocarbons), the heating value as well as other thermophysical properties being dependent on the degree of branching of the carbon chain. Then compare the LHV of natural gas thus calculated with that calculated from the HHV.

Solution

Since ideal gas behavior is being assumed, the composition on a mole basis is the same as that on a volume basis. The volume percent data in Table 1.2 does not quite add up to 100% and it will be assumed that the unreported values correspond to noncombustible components.

The contribution of each component i to the LHV and the HHV are given by $y_i * \text{LHV}$ and $y_i * \text{HHV}$ as tabulated in Table 1.3, resulting in a mixture LHV = 35,290 kJ/Sm^3 and HHV = 39,081 kJ/Sm^3.

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[2] At 15°C and 1 atm pressure used by natural gas suppliers in Europe and South America while normal m^3 (Nm^3) that is measured at 0°C and 1 atm pressure.

TABLE 1.3 Summary of heating value calculations

	From volume %	Given		Calculated		
	Mole %	LHV	HHV	$y_i \times$ LHV	$y_i \times$ HHV	H_2O formed by combustion
Component	100 y_i	kJ/Sm^3		kJ/Sm^3		Sm^3/Sm^3 of natural gas
CH_4	93	34,064	37,799	31,680	35,153	1.860
C_2H_6	3	61,220	66,853	1,837	2,006	0.090
C_3H_8	1	88,975	96,623	890	966	0.040
n-C_4H_{10}	0.5	116,134	125,722	581	629	0.025
n-C_5H_{12}	0.1	138,369	149,822	138	150	0.006
n-C_6H_{14}	0.1	164,595	177,652	165	178	0.007
$N_2 + CO_2$ + other noncombustibles	2.3	—	—	0	0	—
Total	100.0			35,290	39,081	2.028

In order to calculate the LHV from the preceding value of HHV, the amount of water formed by the complete oxidation of the combustibles is required, and the volumetric or molar contribution of each component i to form H_2O is given by $y_i * m/2$ where m is the number of H atoms in component i as tabulated in the last column of Table 1.3, resulting in a total amount of 2.028 Sm^3 H_2O formed per standard cubic meter of natural gas. Next, using the latent heat of H_2O as 2464 kJ/kg obtained from steam tables (e.g., Keenan et al., 1969) at the standard temperature of 15°C where the molar volume of an ideal gas is 23.64 Sm^3/kmol at a pressure of 1 atm:

$$\text{LHV} = \text{HHV} - \frac{2.028\ \text{Sm}^3/\text{Sm}^3}{23.64\ \text{Sm}^3/\text{kmol}} \times 2{,}464\ \text{kJ/kg} \times 18.015\ \text{kg/kmol} = 35{,}373\text{kJ/Sm}^3$$

This value compares well with the value of 35, 290kJ/Sm^3 shown in Table 1.3.

1.1.1.2 Petroleum Although petroleum resources occur to some degree in most parts of the world, the major commercially valuable resources occur in relatively fewer locations where appropriate geological conditions prevailed for the formation and storage of these fuels underground. It is widely accepted that the formation of petroleum (the word derived from Latin: petra = rock, oleum = oil) was biogenic in nature since petroleum deposits are found almost exclusively in sedimentary rock formations laid down millions of years ago when life flourished on the planet.

Petroleum is a mixture of various hydrocarbons with some sulfur, nitrogen, and organometallic compounds also present. A number of processing steps are involved in a refinery to produce the various high-value salable fuel streams such as gasoline, diesel, and jet fuel from the petroleum, the major processing step being the distillation operation. The petroleum distillation operation does not separate out individual compounds but produces various fractions consisting of mixtures. For example, fuel oil typically contains some 300 individual compounds. In fact petroleum as well as the various fuel products derived from petroleum are characterized by their boiling point curve rather than their chemical composition. This curve is generated by placing a known volume (100 ml) of sample in a round-bottom flask with means to collect and condense the vapor formed when it is heated at a specified rate. The vapor temperature when the first drop of condensate is collected is recorded as the "initial boiling point" as well as when the volume of vapor collected is 5, 10, 15, 20 ml, after which at every subsequent 10-ml interval to 80 ml, and finally at every subsequent 5 ml, and at the end of the test, which is recorded as the "end point" where no more evaporation occurs. Note that the residue remaining in the flask can decompose if the temperature continues to increase.

The petroleum received at the refinery is treated in a desalter to wash out salts before it is processed in the distillation unit operating near atmospheric pressure. The residual bottoms from this distillation unit may be fed to a vacuum distillation unit to maximize recovery of the valuable lower boiling point components. Two primary classes of liquid fuels are produced in a refinery, distillates, and residuals. Distillates are composed entirely of vaporized material from the petroleum distillation operation (subsequently condensed) and are clean, free of sediment, relatively low in viscosity, and free of inorganic ash. Gasoline, kerosene, or jet fuel and diesel are all distillates. Residuals contain fractions that were not vaporized in the distillation operation and contain inorganic ash components (that originate from the petroleum) and have higher viscosity such as heavy fuel oil. In addition to the gasoline, kerosene, diesel, and fuel oil fractions, other fractions having lower boiling points separated out by distillation include the following:

- A gaseous stream that is a mixture of primarily straight chain hydrocarbons, with an average carbon number of about 4 (the number of C atoms in a molecule) and is marketed as liquefied petroleum gas (LPG) after desulfurization, which may be accomplished using an amine process similar to desulfurization of natural gas.
- Naphtha that is a mixture of primarily straight chain hydrocarbons, with 5–12 carbon atoms and is supplied to a catalytic reforming process to increase its octane rating by rearranging the structure of the hydrocarbons. The naphtha is first hydrotreated (catalytically reacted with H_2 at high pressure) to form H_2S from the sulfur compounds, which is then followed by desulfurization before it is fed to the reforming process to protect the catalyst in the reformer.

The LPG, gasoline, kerosene, diesel, and fuel oil fractions are also further processed, to meet the required product specifications before they leave the refinery, which include removal of sulfur, nitrogen (their oxides formed by combustion being pollutants), and oxygen. These processing steps may include a Merox unit that assists in the desulfurization process by deoxidizing the mercaptans to organic disulfides; a hydrocracker unit that uses hydrogen to upgrade heavier fractions into lighter, more valuable products; a visbreaking unit that upgrades heavy residual oils by thermally cracking them into lighter, more valuable reduced viscosity products; an alkylation unit that uses H_2SO_4 or HCl as a catalyst to produce high octane components suitable for gasoline blending; a dimerization unit to convert olefins into higher octane gasoline blending components; an isomerization unit to convert straight chained to higher octane branched chained molecules again suitable as gasoline components; and a coking unit that can process very heavy residual oils to make additional gasoline and diesel while forming petroleum coke as a residual product. Depending on the purity (i.e., its S and metals such Va and Ni content) and type of process producing the petroleum coke, it can either be a valuable product suitable for making electrodes or may be used as a solid fuel like coal. A boiler plant utilizing the coke, however, should be designed to take into account its impurities by installing suitable flue gas treatment processes as well as disposing the ash in an environmentally responsible manner.

Petroleum-derived liquid fuels have become the major sources of energy in many countries because of the availability and convenience of these fuels for transportation engines (gasoline, kerosene, and diesel) and also sometimes for stationary power plants (fuel oils).

The U.S. Energy Information Administration's (2014) estimates of remaining recoverable petroleum in 2012 were the highest for Saudi Arabia at 267×10^9 bbl followed by Venezuela and the United States both at about 211×10^9 bbl while on a worldwide basis, the total was 1526×10^9 bbl (1 bbl is equivalent to 5.8×10^6 BTU or 6.1 GJ on a HHV basis). To put these numbers in perspective, the consumption rate of petroleum in the year 2012 was 89×10^6 bbl/day.

In order to maximize the production of the more valuable products as well as desulfurized and denitrified products, a number of processes are included downstream of the petroleum distillation operation. An example is hydrotreating to desulfurize, denitrify, and deoxygenate.

Catalytic reforming is a chemical process used to convert petroleum refinery naphthas, typically having low octane ratings, into high-octane liquid products called reformates, which are components of high-octane gasoline (also known as petrol). Basically, the process rearranges or restructures the hydrocarbon molecules in the naphtha feedstocks as well as breaks some of the molecules into smaller molecules. The overall effect is that the product reformate contains hydrocarbons with more complex molecular shapes having higher octane values than the hydrocarbons in the naphtha feedstock. In so doing, the process separates hydrogen atoms from the hydrocarbon molecules and produces very significant amounts of byproduct hydrogen gas for use in a number of the other processes involved in a modern petroleum refinery. Other byproducts are small amounts of methane, ethane, propane, and butanes.

1.1.1.3 Coal Coal is the most heterogeneous among all the fossil fuels. It was formed from plant life under the action of immense pressures and temperatures prevailing within the earth's crust and in the absence of air over time frames encompassing millions of years. The major element present in the "organic portion" of coal is carbon, with lesser amounts of hydrogen, oxygen, nitrogen, and sulfur. Sulfur mostly as iron pyrite is also present as part of the "inorganic portion" or ash in the coal that includes compounds of aluminum, silicon, iron, alkaline earths, and alkalis. Coal also contains some chlorine, mercury, and other volatile metals. The composition of coal is expressed by its "ultimate analysis" and by its "proximate analysis." The ultimate analysis provides the elemental analysis of the organic portion of coal along with the moisture content (if reported on a wet basis), ash content, and the sulfur content. The sulfur forms may also be reported, that is, the fractions that are part of the organic and the inorganic portions of the coal. The inorganic portion may be further subdivided into that present as a sulfide ("pyritic" since it is typically present as FeS_2) and as a sulfate. The proximate analysis shows the "fixed carbon," "volatile matter," moisture, and ash contents. Fixed carbon and volatile matter together constitute the organic portion of the coal with the volatile matter being that fraction that evolves when the coal is heated in the absence of O_2, the residue remaining being carbon (fixed carbon) and the inorganic constituents. The volatile matter content is typically an indicator of the reactivity and ease of ignition and affects the furnace design, for example, higher volatile matter increases flame length while affecting the amount of secondary air requirement and its distribution. In the case of gasification (partial oxidation to produce a combustible gas as discussed in Chapter 9) under milder temperatures, the volatile matter content provides an indication of the amount of organic components produced such as tars, oils, and gaseous compounds. The ash content is also important in the design of the furnace or the gasifier, pollution control equipment, and ash handling systems. It also affects the efficiency of the furnace or gasifier. The volatile matter is determined by placing a weighed freshly crushed coal sample in a covered crucible and heating it in a furnace at $900 \pm 15°C$ for a specified period of time as specified by the American Society for Testing and Materials (ASTM). The volatile matter is then calculated by subtracting the moisture content of the coal from the loss in weight measured from the preceding heating process. The ash may next be determined by heating the solid remaining in the crucible over a Bunsen burner till all the carbon is burned off (by repeatedly weighing the sample till a constant weight is obtained). The residue is then reported as ash while the fixed carbon is obtained by difference.

Coal is classified according to the degree of metamorphism into the following four types:

1. Anthracite that is low in volatile matter and consists of mostly carbon (fixed carbon).
2. Bituminous that contains significant amounts of the volatile matter and typically exhibits swelling or caking properties when heated.
3. Sub-bituminous that is a younger coal contains significant amounts of volatile matter as well as moisture bound within the remnants of the plant cellular structure ("inherent" moisture).
4. Lignite that is the youngest form of coal, that is, when peat moss is not included in the broader definition of coal types, is very high in inherent moisture content resulting in a much lower heating value than the other types of coals.

TABLE 1.4 Composition of a bituminous and a lignite coal (as received basis)

Coal type	Bituminous	Lignite
Name of coal	Illinois No. 6	N. Dakota Beulah-Zap
Mine	Old ben	Freedom
Proximate analysis (%)[1]		
Moisture	11.12	36.08
Ash	9.7	9.86
Volatile matter	34.99	26.52
Fixed carbon	44.19	27.54
Total	100	100
Ultimate analysis (%)		
Carbon	63.75	39.55
Hydrogen	4.5	2.74
Nitrogen	1.25	0.63
Sulfur	2.51	0.63
Chlorine	0.29	12 ppmw
Ash	9.7	9.86
Moisture	11.12	36.08
Oxygen	6.88	10.51
Total	100	100
Heating value		
HHV (kJ/kg)	27,135	15,391
HHV (Btu/lb)	11,666	6,617
LHV (kJ/kg)	26,172	14,803
LHV (Btu/lb)	11,252	6,364
Trace component(s)		
Mercury (ppm)	0.18	0.116

Table 1.4 presents the composition and heating value data for a bituminous and a lignite coal. As can be seen, the moisture content of the lignite is much higher while its heating value lower. Coal is a highly heterogeneous solid and significant variation in its composition and heating value may be expected for coal supplied from the same formation.

Almost all the coal consumed in the world is for electric power generation by combusting the coal in boilers and generating power through the Rankine steam cycle, that is, generate high pressure steam to power a turbine as described in Chapter 8. Coal is being used to a limited extent in gasification-based plants to produce gas also known as syngas to fuel gas turbine-based combined cycles in an integrated gasification combined cycle (IGCCs) as described in Chapter 9. It is expected that with the introduction of more advanced gas turbines in the future, coal-based IGCC will have a strong economic basis in addition to its superior environmental signature, to compete with boiler-based power plants. The synthesis of chemicals is also being pursued, a majority of such plants being built in China.

The method of coal mining depends on the depth and quality of the coal seams and the local geology. Coal is mined on the surface or underground depending on the depth (surface mining usually when depth is limited to 50 m) and thickness of the coal seam and nature of the overburden. The coal after it is mined, which is called "run of mine" coal, is typically delivered to a coal preparation plant to separate out any rocks as well as machine parts or tools that may be left behind from the mining operation and reduce the inorganic impurities (ash along with the accompanying pyritic sulfur) in order to upgrade its value. Cleaning is accomplished at the current time by physical means (mechanical) separation of the contaminants using differences in the physical properties such as density. Chemical cleaning where the impurities are leached out as well as microbial processes (especially for sulfur removal) are under development.

In physical cleaning, coal is crushed and separated into coarse and fine fractions by a screening operation, the streams thus generated being treated separately. Coal coarser than 12.5 mm may be cleaned in a "heavy medium vessel" by gravity separation. A slurry consisting of suspended fine particles of magnetite or ferrosilicon in water forms the medium with a specific gravity that allows low-density materials like coal particles to float and be separated at the top and inorganic higher density materials to sink. Coal particles in the size range from 1 to 12.5 mm may be cleaned in a heavy medium cyclone that uses the centrifugal force generated by the circular motion to cause separation again based on density. Particles in the size range from 150 μm to 1 mm may be cleaned in a spiral separator that uses in addition to the density, difference in the hydrodynamic properties such as drag. Particles smaller than 150 μm may be cleaned by flotation, which uses primarily the difference in their hydrophobicity enhanced by the use of surfactants and wetting agents. The coal particles adhere to air bubbles induced into the agent and rise to the surface, thereby causing the separation. In addition to frothing agent (e.g., aliphatic or aromatic alcohols, poly glycol ethers) and flocculent (e.g., the water soluble polymer, anionic polyacrylamide), other chemicals are added to assist in the separation such as collectors, activators, depressants, as well as reagents for pH control.

The U.S. Energy Information Administration's (2014) estimates in 2008 of remaining recoverable coal were the highest for the United States at 236×10^9 tonne followed by Russia at 157×10^9 tonne, while on a worldwide basis, the total was 860×10^9 tonne. The annual consumption rate of coal in the year 2011 was 7.4×10^6 tonne. It should be borne in mind, however, that coal from different regions has different energy content. These data indicate that the reserves can last a long time if the current consumption rate continues, which is alarming if the accompanying CO_2 emissions go unchecked and are allowed to build up in the atmosphere.

Example 1.2. Estimate the percentage CO_2 capture (separated from the flue gas for subsequent sequestration) required from a supercritical steam coal fired boiler to result in the same amount of CO_2 emission based on a net MW of electric power produced by the plant as a natural gas fired combined cycle (note that the CO_2 emissions being considered in this example do not represent the emissions on a complete life cycle basis, which can be significant, e.g., in case of coal, does not include mining, cleaning, and transportation). The following data is available for the coal-fired plant and the natural gas-fired plant (note that heat rate is the amount of the energy in the fuel required to produce a unit of electric power and is inversely proportional to the efficiency). Assume the plant net heat rate varies linearly with the percentage CO_2 captured and complete combustion of both the fuels.

Coal-fired boiler plant:
Net heat rate (HHV basis) with no CO_2 capture = 9165 kJ/kWh
Net heat rate (HHV basis) with 90% CO_2 capture = 12,663 kJ/kWh
Coal: Illinois No. 6 bituminous coal with characteristics given in Table 1.4

Natural gas-fired combined cycle plant:
Net heat rate (LHV basis) with no CO_2 capture = 5800 kJ/kWh
Natural gas: with characteristics as calculated in Example 1.1.

Solution

The amount of CO_2 formed by complete combustion of the natural gas is calculated by adding up that formed from each of its constituents as $y_i n$ kmol CO_2/kmol of natural gas, where y_i is the mole fraction of specie i and n is the number of C atoms in that specie. These values are tabulated in Table 1.5 giving a total of 1.056 kmol CO_2/kmol of natural gas.

Next, LHV of natural gas

$$= 35{,}290\,\frac{\text{kJ}}{\text{Sm}^3}\,(\text{from Example 1.1}) = 35{,}290\frac{\text{kJ}}{\text{Sm}^3}\times\frac{22.414\,\text{Nm}^3}{\text{kmol}}$$

$$\times\frac{(273.18+15)^\circ\text{K}}{(273.18+0)^\circ\text{K}}\frac{\text{Sm}^3}{\text{Nm}^3} = 834{,}422\,\frac{\text{kJ}}{\text{kmol of natural gas}}.$$

Then CO_2 emitted by natural gas combustion

$$= 1.056\frac{\text{kmol}}{\text{kmol}}\times 5{,}800\frac{\text{kJ}}{\text{kWh}}\times 1{,}000\frac{\text{kW}}{\text{MW}}\bigg/\left(834{,}422\,\frac{\text{kJ}}{\text{kmol}}\right) = 0.007340\frac{\text{kmol}}{\text{MWh}}.$$

TABLE 1.5 Calculated amount of CO_2 formed by complete combustion

Component	Mole % 100 y_i	CO_2 formed by combustion kmol/kmol of natural gas
CH_4	93	0.930
C_2H_6	3	0.060
C_3H_8	1	0.030
n-C_4H_{10}	0.5	0.020
n-C_5H_{12}	0.1	0.005
n-C_6H_{14}	0.1	0.006
CO_2	0.5	0.005
N_2 + other noncombustibles	1.8	0
Total	100.0	1.056

The amount of CO_2 formed by complete combustion of the coal is calculated from the C content of the coal (0.6375 kg/kg of coal).

CO_2 formed by coal combustion $= (0.6375\ \text{kg/kg}/12.011\ \text{kg/kmol}) = 0.05308$ kmol/kg of coal.

CO_2 emitted by coal combustion with 0% capture $= 0.05308\text{kmol/kg}$ of coal $\times$ $9{,}165\text{kJ/kWh} \times 1{,}000\text{kW/MW}\,/(27{,}135\text{kJ/kg}) = 0.01793\text{kmol/MWh}$.

CO_2 emitted by coal combustion with 90% capture $= 0.05308\text{kmol/kg}$ of coal $\times$ $12{,}663\text{kJ/kWh} \times 1{,}000\text{kW/MW}\,/(27{,}135\text{kJ/kg}) \times (1-0.9) = 0.00248\text{kmol/MWh}$.

Then, by linear interpolation between these two values for the CO_2 emitted by coal combustion to obtain the same emission as the natural gas-fired plant, CO_2 capture required for the coal plant = 62%, again not on complete life cycle basis.

1.1.1.4 Oil Shale The organic solids in oil shale rock are a wax-like material called kerogen and the oil is extracted by heating the rock in retorts in the absence of air where the kerogen decomposes forming oil, gas, water, and some carbon residue. The source of the kerogen is again biogenic in nature since most extensive deposits of oil shale are found in what used to be large shallow lakes and seas millions of years ago where subtropical and stagnant conditions favored the growth and accumulation of algae, spores, and pollen. The nitrogen content of shale oil is typically higher than that of petroleum and if left in the fuels produced from shale oil such as gasoline or jet fuel would result in significant emissions of NO and NO_2 (collectively denoted as NO_x). Production of the saleable fuels from the shale oil requires more extensive processing than most petroleum feedstocks. The United States has significant deposits of oil shale concentrated in Colorado and Utah, followed by Russia and Brazil.

1.1.2 Nuclear

The commercial production of power from nuclear energy involves conversion of matter to energy by nuclear fission reactions. These reactions consist of the capture of a neutron by nuclei of fissionable isotopes. Today's commercial nuclear reactors utilize U-235, a fissionable isotope of uranium containing a total of 235 neutrons and protons in its nucleus. Most of today's reactors require a fuel that contains between 3.5 and 5% of U-235 while naturally occurring uranium (which exists in the oxide form within the ore) may contain as little as 0.1% uranium (mostly in the form of U-238, which is not fissile, i.e., does not undergo fission) with only 0.7% of it fissile. So an initial step for preparing a suitable fuel for nuclear reactors consists of producing a concentrated form of uranium, generally containing 80% uranium. The tailings from this concentration process contain long-lived radioactive materials in low concentrations and toxic materials such as heavy metals and must be isolated from the environment. A number of other processing steps are required before nuclear “fuel rods” are produced as explained in Chapter 12.

Safety of nuclear power generation in terms of accidental release of radioactive materials from the reactor to the environment and the safe handling and disposal of the nuclear waste including spent nuclear fuel rods have been major issues. These issues have been impediments to the widespread use of nuclear energy in many countries. France, however, has been an exception where a majority of its electricity is generated by nuclear fission.

Nuclear power generation has a significantly smaller carbon footprint when compared to fossil-fueled power generation on a total life cycle basis that has led to a renewed interest in building nuclear power plants in a number of countries while incorporating design improvements based on lessons learned from previous nuclear power plant accidents.

The Joint Report by the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency and the International Atomic Energy Agency (Uranium 2011: Resources, Production and Demand, 2012) shows current estimates of remaining recoverable uranium ore if priced less than $130/kg are the highest for Australia at 1,661,000 tonne followed by Kazakhstan at 629,000 tonne, while on a worldwide basis the total is 5,327,200 tonne. At the current consumption rate, the supply is sufficient for another 100 years.

1.1.3 Renewables

1.1.3.1 Biomass and Municipal Solid Waste All living plant matter as well as organic wastes derived from plants, humans, animals, and marine life represent sources of energy that when properly managed and utilized can make a significant contribution toward conserving our finite energy resources of fossil and nuclear fuels, and more importantly have an impact on the global greenhouse gas emissions.

Specific examples of biomass are agricultural residues, trees, and grasses specifically grown for harvesting as energy crops, forestry residues, urban wood waste and mill residues, paper industry waste sludges, sewage, and animal farm wastes. These wastes or residues as well as municipal solid wastes in many instances pose a disposal problem while having significant energy content. The main driving force for utilizing plant-derived biomass as an energy source is its near CO_2 neutrality. Complete CO_2 neutrality would entail the growth rate of such biomass exactly balances the release rate of CO_2 but consideration of the CO_2 emissions associated with any fossil fuels utilized to synthesize fertilizers and other farm chemicals required to grow the biomass, as well as collecting, and any drying and transporting of the biomass should be taken into account. Growth of biomass by photosynthesis is a natural solar energy-driven CO_2 sink but the relative time scales of growth and utilization should be taken into account, however, when considering energy crops. For example, harvesting old growth trees for fuel should not be considered for energy use while fast-growing fuel crops, agricultural residues, and waste wood should. Agricultural residues are generated after each harvesting cycle of commodity crops and a portion of remaining stalks and biomass material is left on the ground, which can be collected.

Residues of wheat straw and corn stover make up the majority of crop residues but their value as a fertilizer when ploughed back into the soil should be taken into account. Energy crops that are produced solely or primarily for use as feedstocks in energy generation processes include hybrid poplar, hybrid willow, and switchgrass but should be grown on land without competing with food production. Potential environmental issues of growing energy crops that should be taken into consideration include loss of biodiversity due to growing only one plant specie for multiple crop cycles as well as fertilizer contamination of ecosystems.

Forestry residues include biomass material remaining in forests that have been harvested for timber. Timber harvesting operations do not extract all biomass material because only timber of certain quality is usable in processing facilities and thus a significant amount of residual material after timber harvest is potentially available for energy generation purposes. These forestry residues are composed of logging residues, rough rotten salvageable dead wood, and excess small pole trees. Urban wood waste and mill residues include waste woods from manufacturing operations that would otherwise be landfilled such as mill residues, pallets, construction waste, and demolition debris.[3]

In the paper industry, wood or other cellulosic raw materials are digested with alkali chemicals under high temperature and pressure to separate cellulosic fibers of wood from binders (lignins, resins) and the spent (black) liquor is currently regenerated by incineration in special "recovery" boilers with the addition of $Na(SO_4)_2$ while also recovering its energy value. Gasification of the black liquor is another option being considered. In the paper recycling industry, waste paper is received and de-inked prior to recovery of the fiber generating a sludge that contains particles of ink and fibers too short to be converted to finished paper product. This waste stream can also be utilized for energy recovery.

Biomass may be combusted in specially designed boilers, or gasified to generate a gas that could be utilized to generate power in internal combustion engines or fuel cells. Co-utilization of biomass along with coal in larger scale power generation facilities to realize economies of scale is gaining much interest. Combustion of waste streams such as municipal solid waste, treated wood, and plastics, especially those containing chlorine, could, however, produce highly toxic pollutants such as dioxins and furans (described later in this chapter) and proper design measures should be taken to limit these emissions.

Biomass as a renewable energy source provided about 50 EJ/year or 10% of global total primary energy supply in 2008 while it accounted for less than 4% of the total energy usage in the United States in 2009. The technical potential for biomass-derived energy may be as high as 500 EJ/year by 2050 (Edenhofer et al., 2011). Table 1.6 shows the composition and heating value data for woody biomass and covered field dried switchgrass alongside those for a bituminous coal. As can be seen, the heating value of the biomass is significantly lower than that of the coal. The moisture content

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[3] Chemically treated construction waste wood may give rise to pollutants during combustion, their source being the treatment chemicals used, and proper pollution abatement measures should be designed into the plant scheme.

TABLE 1.6 Biomass versus coal characteristics

	Woody biomass		Switchgrass		Bituminous coal	
Basis	Dry	As received	Dry	As received	Dry	As received
Ultimate analysis (%)						
Carbon	52.36	26.18	42.60	36.21	71.72	63.75
Hydrogen	5.60	2.80	6.55	5.57	5.06	4.5
Nitrogen	0.37	0.19	1.31	1.11	1.41	1.25
Sulfur	0.03	0.02	0.01	0.01	2.82	2.51
Chlorine	0.10	0.05	0.04	0.03	0.33	0.29
Ash	1.38	0.69	7.41	6.30	10.91	9.7
Moisture	0.00	50.00	0.00	15.00[a]	0	11.12
Oxygen	40.16	20.08	42.08	35.77	7.75	6.88
Total	100.00	100.00	100.00	100.00	100.00	100.00
Heating value						
HHV (kJ/kg)	19,627	9,813	18,113	15,396	30,531	27,135
HHV (Btu/lb)	8,438	4,219	7,787	6,619	13,126	11,666
LHV (kJ/kg)	18,464	9,232	16,659	14,161	29,568	26,172
LHV (Btu/lb)	7,938	3,969	7,162	6,088	12,712	11,252

[a] Covered field dried.

of biomass is typically much higher than bituminous coals unless the biomass has been dried as was the case with the switchgrass.

Example 1.3. Express the equivalent thermal energy required for drying as received woody biomass to the same moisture content as the as received bituminous coal with characteristics shown in Table 1.6, as a percentage of HHV of the as received biomass. Assume the equivalent biomass contained energy required for the drying operation is 2400 kJ/kg of water evaporated (a steam-heated dryer is assumed and includes the electric energy used in the drying operation converted to an equivalent thermal energy).

Solution

Biomass moisture on an as-received basis = 50%.

Biomass moisture after drying = 11.12%.

Moisture removed $= 0.5 - (0.1112/1 - 0.1112) \times (1 - 0.5) = 0.4374$ kg H_2O/kg as received biomass.

Total equivalent fuel for drying $= (0.4374\ \text{kg}\,H_2O/\text{kg as received biomass})(2400\ \text{kJ}/\text{kg}\,H_2O) = 1050$ kJ/kg as received biomass.

HHV of biomass = 27,135 kJ/kg as received.

Total equivalent fuel for drying as percentage of HHV in biomass $= (1{,}050\ \text{kJ}/\text{kg}/27{,}135\ \text{kJ}/\text{kg}) \times 100\% = 3.87\%$.

1.1.3.2 Hydroelectric This is the most widely used form of renewable energy and accounted for more than16% of global electricity usage in 2008 while the total resource potential is 14,576 TWh/year (Edenhofer et al., 2011). It accounted for 2.7% of the total energy usage in the United States in 2009. This resource became important in modern times with the development of efficient electric generators and transmission technology that allow the transmission of electricity over vast distances from remotely located hydroelectric plants to the energy users several hundred miles away.

The energy that may be recovered from flowing water depends on the quantity of flow of water and the hydrostatic head, which is the height through which the water can be made to flow from the reservoir created by a dam to a hydraulic turbine. The construction of diversion and storage dams for such hydroelectric power plants thus requires suitable topography and other site conditions, and a steep drop in the elevation of the river. The environmental effects of submerging large areas of land by the construction of the dam can be devastating unless such projects are properly planned to minimize the impact on local human population as well as the flora and fauna. Hydroelectric plants are capital intensive but the operating costs are low since there is no fuel cost associated with such plants.

1.1.3.3 Solar Approximately half of the solar energy reaching earth's outer atmosphere reaches the earth's surface, while the remainder consists of the fraction absorbed by the atmosphere and the fraction reflected back into space. A portion of the energy reaching the surface ends up in biomass as chemical bond energy, in wind and waves as kinetic energy, in rivers as potential energy, and in oceans to create thermal gradients. These all represent renewable energy resources, but direct use of solar energy is being implemented more and more in recent times for heating and for conversion into electricity directly using solar photovoltaic cells and through the Carnot cycle using heat engines described in Chapter 12.

The potential for producing electric power from solar energy is huge with estimates ranging from 1,580 to 49,800 EJ/year, roughly equivalent to as much 3–100 times the world's primary energy usage in 2008 (Edenhofer et al., 2011) while it accounted for less than 0.1% of the total energy usage in the United States in 2009.

1.1.3.4 Wind Wind, which is the movement of air across the surface of the earth, is caused by pressure gradients. These result from the surface of the earth being heated unevenly by the sun. Heating by the sun varies with (i) latitude because the angle of incidence of the sun's rays varies with latitude as well as (ii) the earth's surface properties such as reflectivity and absorptivity (e.g., whether it is covered by ocean or dry land and whether it has vegetation), and of course (iii) time of day. The distribution of wind is not uniform over the earth; wind resources are higher in polar and temperate zones than in tropical zones and are also higher in coastal areas than inland. Furthermore, the drag on the atmosphere caused by earth's rotation results in turbulence, giving rise to a varying pattern of wind across the earth's surface.

Only a small fraction of the available wind energy resource is currently being harnessed. Wind energy is harnessed by installing rotating machines that are typically propellers called "wind mills" that are connected to electric generators as discussed in Chapter 12. Winds only in certain speed ranges may be harnessed economically at the current time. Because of friction losses, wind power turbines usually do not operate at wind velocities much lower than approximately 16 km/h, while the rotors of wind turbines are usually feathered (designed to vary blade pitch) to prevent damage at very high wind speeds such as winds of gale force.

The global potential for generating electricity from wind is very large, with estimates ranging from 70 EJ/year (19,400 TWh/year) for onshore installations to 450 EJ/year (125,000 TWh/year) for onshore and near-shore installations, while those for shallow offshore installations range from 15 EJ/year to 130 EJ/year (4,000 to 37,000 TWh/year) when only considering relatively shallower and near-shore applications. Wind, however, accounted for only 0.72% of the total energy usage in the United States in 2009.

1.1.3.5 Geothermal Geothermal energy is the heat energy stored within the earth's crust. The earth's core maintains temperatures in excess of 5000°C due to the heat generated from gradual radioactive decay of elements. It was previously thought incorrectly that the heat was left over from planet's formation but calculations have shown that the earth's core would have cooled down a long time ago. The heat within the core flows continuously to the earth's surface by conductive transfer and convective transfer by molten mantle beneath the crust. The heat intensity tends to be strongest along tectonic plate boundaries. Volcanic activity transports hot material to near surface but only a small fraction of molten rock actually reaches the surface while most of it is left at depths of 5–20 km beneath the surface. The heat is then transported to the surface by hydrological convection by groundwater, hot springs and geysers being examples. Until the beginning of the last century, the utilization of geothermal heat was limited to use as warm water, Roman baths in England being early examples. Also, geothermal hot springs began to enjoy widespread use throughout the world as therapeutic treatment. Only in more recent times has there been more extensive use made of geothermal energy for both power and nonpower applications. Typically, the useful geothermal heat for electric power generation is available in the form of hot brine with temperatures ranging from 150 to 200°C and discussed in more detail in Chapter 12.

World potential for electricity generation from the more suitable higher temperature geothermal energy is 33,600 TWh/year and that for heating from the lower temperature geothermal energy is greater than 1400 TWh/year, while it accounted for only 0.2% of the total energy usage in the United States in 2009.

1.2 ENERGY AND THE ENVIRONMENT

Energy is used in almost every human activity in an industrialized society, examples being transportation (automobiles, busses, trucks, trains, aircraft, rockets), household uses (cooking, hot water, air conditioning), agriculture (production of fertilizers, pumping of water), and manufacturing (heating, electricity). Thus, energy is consumed by us directly as in transportation and household uses as well as indirectly by consuming goods that require energy in their production. Energy usage can be a direct measure of the economic well-being of a society since it plays such an important role in our lives. The per capita energy use is often correlated to the per capita gross national product of a country and the trend line based on data for several countries shows essentially a straight line. Strictly speaking, this correlation should be corrected for other factors such as the energy usage efficiency of a given country as well as its climatic conditions and the type of economy it has, that is, whether it is dominated by a service economy, agriculture, or industrial production. Energy conservation measures practiced by or instituted in a given country such as mass transportation and the severity of the climate, that is, whether heating and/or cooling are required, can all affect the energy usage. In any case, it should be the goal of every country, both developing and developed, to practice energy conservation in order to reduce the slope of the energy usage trend line so that we have a planet that can sustain itself.

Energy use over the next two decades is expected to increase significantly throughout the world, with highest growth rates in Asia. The world energy consumption is projected to be about 20% higher in 2020 and almost 60% higher by 2040 over the 2010 values. More than 85% of the increase in this energy demand is due the developing nations driven by strong economic growth and expanding populations (U.S. Energy Information Administration, 2013b). Fossil fuels (liquid fuels, natural gas, and coal) are projected to supply most of the world's energy, as much as three-fourths of total world energy consumption in 2040.

World use of petroleum and other liquid fuels is expected to grow by more than 30% by 2040 over the 2010 values. The world's total natural gas consumption is expected to increase by more than 60% by 2040 over the 2010 values due to increasing supplies of natural gas, particularly from shale formations. Coal is expected to continue playing a significant role in the world energy markets, especially in the developing countries of Asia with world coal consumption increasing by almost 50% by 2040 over the 2010 values. Due to these significant increases in fossil fuel usage worldwide, the greenhouse gas CO_2 emissions to the atmosphere are expected to increase by an average annual growth of 1.3% in the 2010–2040 period or by as much as 46% by 2040 over the 2010 level. In addition to this greenhouse gas, the harnessing of the energy contained within a fuel by combustion produces pollutants such as oxides of sulfur, oxides of nitrogen, and unburned hydrocarbons that are introduced into the atmosphere, the amount depending on the degree of pollution abatement measures incorporated. A conflict thus arises between increasing the standard of living (measured in terms of per capita gross national product) and per capita energy use that can have a direct impact on the environment unless sustainable energy management is pursued.

1.2.1 Criteria and Other Air Pollutants

Criteria pollutants as defined by the U.S. Environmental Protection Agency (U.S. EPA) consist of CO, SO_2 and SO_3, NO and NO_2, O_3, Pb, and particulate matter

(PM). These pollutants are commonly found all over the United States and thus may be considered as indicators of air quality.

1.2.1.1 Carbon Monoxide and Organic Compounds CO along with another set of harmful pollutants consisting of organic compounds are formed due to improper combustion of carbonaceous fuels and can be minimized by designing the combustion process with good mixing (turbulence) of the fuel with the oxidant (air), and providing enough residence time at high temperatures. The following describes the mechanism of CO formation during combustion of natural gas.

The CH_4 molecule is very stable and requires high energy atoms to break loose an H atom forming the CH_3 radical that plays a key role in propagating the combustion process. This process includes the partial oxidation of CH_4, oxidation of CO and OH reactions. CO formation involves a number of steps but is a fast overall reaction while the oxidation of CO to CO_2 is very slow and as a result, the reciprocating engine produces significant amounts of CO due to the short residence time. In a gas turbine however, more residence time is available within the combustor and the CO emissions are much lower. High temperatures and O_2 concentrations and large residence times are required for the CO oxidation that involves the reaction with the OH radical formed during the combustion process. High CO emission not only means more pollution but also lower overall plant efficiency.

Postcombustion control may include oxidation of the CO as well as the volatile organic compounds (VOCs) in the presence of a noble metal catalyst. The harmful health effects of CO include reduction of O_2 supply to the organs such as the heart and brain as well as to the tissues while extremely high levels of CO can cause death. VOCs are responsible for the formation of a number of secondary pollutants such as peroxyacyl nitrates (PANs), which are powerful respiratory and eye irritants. They are also responsible for the formation of a major portion of the tropospheric O_3 such as in less polluted rural areas where the direct NO emissions and concentrations may be low.

Another set of toxic organic compounds that are also emitted depending on the type of fuel (its Cl content) belong to the families of compounds known as dioxins and furans, and among all of these compounds, 2,3,7,8-tetrachloro-*p*-dibenzo-dioxin (2,3,7,8TCDD) is considered the most toxic. These compounds can enter the body through air and water but mostly through food and build up in the fatty tissues. The U.S. EPA has stated that 2,3,7,8TCDD is likely to be a cancer-causing substance to humans. In addition, exposure to dioxins and furans changes hormone levels while high doses of dioxin have caused a skin disease called chloracne. Animal studies have shown that exposure to dioxins and furans changes their hormone systems, development of the fetus, decreased ability to reproduce, and suppresses the immune system. The formation of these compounds downstream of the combustion process may be minimized by quickly cooling the flue gas and by limiting the use of certain metals that are known to promote or catalyze their formation in the downstream equipment.

1.2.1.2 Sulfur Oxides About 90% of the sulfur oxides emitted during the combustion of a sulfur-bearing fuel is in the form of SO_2 with the remainder being SO_3. These oxides are collectively denoted as SO_x. Postcombustion capture of the SO_x from stationary sources is accomplished at the present time by reaction with Ca or Mg containing compounds such as limestone (or lime) and dolomite to form the corresponding sulfites that are then oxidized using air to form the stable sulfates. In high temperature gasification process, the sulfur in the fuel is mostly converted into H_2S and some COS and only minor amounts of CS_2 and mercaptans. COS is hydrolyzed to H_2S by catalytically reacting the H_2S with H_2O after which the H_2S is removed using either a chemical or physical solvent to eventually produce byproduct elemental sulfur or H_2SO_4. These processes are discussed in more detail in Chapters 8 and 9. The environmental effects of SO_x include the formation of H_2SO_4 in atmosphere under action of light, which reduces the pH of the rain water giving rise to "acid rain." Acid rain reduces soil productivity by causing damage to vegetation. It also causes damage to aquatic life and gives rise to the formation of sulfate particulates, mostly H_2SO_4 and $(NH_4)_2SO_4$.

1.2.1.3 Nitrogen Oxides NO is the primary product of combustion and is formed via three routes. The NO is produced from (1) high temperature oxidation of molecular N_2 (thermal NO), (2) hydrocarbon radical attack on the molecular N_2 (prompt NO), and (3) oxidation of chemically bound nitrogen in the fuel (fuel NO). The thermal NO, that is, the formation of NO from the N_2 present in the combustion air, requires the breaking of the covalent triple bond in the N_2 and requires very high temperatures and forms by the action of the O radical produced at high temperatures during the combustion process. Increased temperature, residence time, and O_2 concentration increase NO emission, which is in direct contrast to the conditions required for CO formation. As much as 60–80% of the fuel-bound nitrogen in fuels such as oil and coal forms NO. The formation of NO_2 is not significant during the combustion process, however the NO oxidizes to NO_2 in the atmosphere and thus all NO is potential NO_2. Another oxide of nitrogen, N_2O, which is also formed during combustion, has become important in recent years due to its role in the stratosphere as a greenhouse gas. It is formed in significant concentrations (from an environmental impact standpoint) in fluidized bed combustion.

Postcombustion control consists of reducing the NO by reacting with NH_3 or urea as discussed in more detail in Chapters 8 and 9. Prompt NO formed by the mechanism of hydrocarbon radical (formed during combustion) attack on N_2 is typically less than 5%. NO which oxidizes to form NO_2 in the atmosphere, can oxidize O_2 to the pollutant, O_3 under the action of sunlight. NO can also react with hydrocarbon free radicals present in the atmosphere to form components of smog while NO_2 can react with H_2O to form acid rain. Photolysis (decomposition under the presence of sunlight) of HNO_2 produces the OH radical. The reactive OH radical plays a dominant role during the daytime (while the nitrate NO_3 radical plays a major role in the night time) in the formation of photochemical air pollutants, acid rain and fogs, and toxic organics. Possible control strategies for N_2O which is a more potent greenhouse gas than CO_2 include burning of a gaseous fuel in the freeboard or cyclone of the fluidized bed, increasing bed temperatures, decreasing excess air, or catalytic reduction with metal oxides.

The thermal NO formation reaction suddenly takes off around 1540°C and thus a window of opportunity exists to control NO by staying just below this temperature during the combustion process. Thermal NO formation shows an inverse relationship with respect to hydrocarbon and CO emissions when the air to fuel ratio is varied. Control strategies include (i) burning under lean (high excess air) conditions, (ii) staged combustion with rapid quenching of the flame by the secondary air, (iii) premixed burners (ideally, with variable geometry for varying load of the boiler or engine), and (iv) flue gas recycle. Postcombustion processes are also sometimes applied but have certain disadvantages such as transforming NO into other undesirable species. To meet the ultra-low NO_x emissions being mandated, the internal structure of the combustion process that is complex and combines fluid dynamics, turbulent mixing, high temperature chemistry, and heat transfer need to be understood to develop new solutions without compromising efficiency at full or partial combustor load.

1.2.1.4 Ozone O_3 by itself can cause breathing problems as well as eye, nose, and throat irritation aggravating chronic diseases such as asthma, bronchitis, and emphysema. Heart disease and speeding up the aging process of lung tissue as well as a reduction in the resistance to fight off colds and pneumonia may also be consequences. It is also a major source of the OH radical in the atmosphere; under the action of light O_3 decomposes to generate the atomic O that reacts with H_2O to produce the OH radical.

1.2.1.5 Lead Pb accumulates in the body and can cause damage to the brain as well as the nervous system damage. It can lead to mental retardation especially in children and also to digestive problems; some of the chemicals containing Pb are known to have caused cancer in test animals. A major source of Pb entering the atmosphere was leaded gasoline that has been phased out in many countries. An organo Pb compound was added as an anti-knocking agent. Paints utilized pigments made out of Pb compounds and old houses could contain such paints. Plants to recover energy from construction debris should take this into account in their design. Electrodes made out of Pb and PbO_2 are used in storage batteries and recycling of the batteries is extremely important to limit the introduction of Pb into the environment (note that at the present time, batteries are utilized to store the electricity generated by small-scale intermittent renewables, especially by solar photovoltaic cells). Furthermore, proper control methods should be instituted at Pb manufacturing facilities and in Pb smelting processes.

1.2.1.6 Particulate Matter PM can be in solid or droplet (aerosol) form. Increased levels of fine particles in air are linked to heart disease, altered lung function, and lung cancer. Particles of approximately 10 μm or less (PM10[4]) can penetrate deepest parts of lungs while particles smaller than 2.5 μm (PM2.5) tend to penetrate into gas

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[4] The International Organization of Standardization (ISO), which is an international body for setting standards composed of representatives from various national standards organizations, defines PM10 as particulate matter in which 50% of particles have an aerodynamic diameter less than 10 μm. The aerodynamic diameter of an irregularly shaped particle is defined as the diameter of a spherical particle with a density of 1000 kg/m^3 having the same settling velocity as the irregularly shaped particle.

exchange regions of lungs, can cause hardening of arteries, and can lead to heart attacks and other cardiovascular problems. Particles less than 100 nanometers may pass through lungs to affect other organs. Depending on the chemical nature of the particulates, they can also cause cell mutations, reproductive problems, and certain cancers. Sources of particulates can be coal (and to a lesser extent oil and natural gas) fired power and industrial plants, vehicles, especially those burning diesel as well as agriculture during plowing and burning off fields. Various types of filtration devices are utilized to filter out particulates and in the case of power plants burning a fuel such as coal, electrostatic precipitators are sometimes utilized instead of filtration devices called baghouses, as discussed in more detail in Chapter 8.

1.2.1.7 Mercury Hg can enter the food chain especially through aquatic organisms and exposure to it can cause neurological disorders. Studies have shown that Hg exposure can also cause cardiovascular problems. A major portion of the anthropogenic (human-caused) emissions of Hg is from the use of coal as a fuel. Other sources of Hg emissions include cement manufacture and the minerals processing industry. Hg can be repeatedly released into the environment after being first emitted into the atmosphere by entering the food chain. Activated carbon has been found to be an excellent Hg sorbent but its application in coal combustion-based power plants is in its early stages; its effectiveness under different conditions of fuel properties, flue gas temperatures, and trace-gas constituents is being investigated. In coal gasification-based plants, however, a sulfided activated carbon has been proven to be very effective in removing greater than 90% of the Hg from the syngas.

1.2.2 Carbon Dioxide Emissions, Capture, and Storage

The greenhouse gas concentrations of CO_2, CH_4, and N_2O in the atmosphere at the present time far exceed preindustrial values of the mid-eighteenth century due to human activities. CO_2 due to its much higher concentration in the atmosphere plays a more significant role as a greenhouse gas although the CH_4, N_2O as well as halocarbons should not be ignored. Currently, fossil fuel usage for energy recovery is the major source of CO_2 emissions on a worldwide basis, especially power plants firing coal and automobiles burning petroleum-derived fuels while the supply of primary energy is expected to be dominated by fossil fuels until at least the middle of the century. According to the U.S. Energy Information Administration, under the scenario where no new legislation or policies are passed to affect energy markets, the global energy use by 2035 will have grown by more than 50% over the 2008 value. This growth in energy use is fueled by projected rise in income and population in the developing world and fossil fuels are expected to continue playing the major role. In 1992, international concern over global climate change led to the United Nations Framework Convention on Climate Change whose ultimate objective is to stabilize greenhouse gas concentrations in the atmosphere at such a level that dangerous anthropogenic interference with the climate system is prevented.

The United Nations Intergovernmental Panel on Climate Change (IPCC) in their 2007 Fourth Assessment Report indicate that during the twenty-first century, the global surface temperature is likely to rise by 1.1–2.9°C for the lowest greenhouse gas emissions scenario and 2.4–6.4°C for the highest greenhouse gas emissions scenario based on projections made by different climate models. These models differ in sensitivity to greenhouse gas concentrations but the effects such as increases in wind intensity leading to higher and more intense hurricanes, increases of both drought and heavy precipitation, and decline of permafrost coverage are quite concerning. In fact, on the average, mountain glaciers and snow cover have already declined. Sea levels will continue to rise from the melting of land-based ice sheets while ocean warming will magnify this problem since seawater will expand as its temperature increases. The effect of higher concentrations of another "greenhouse gas," H_2O vapor in the atmosphere resulting from warmer oceans and air further compounds the challenge.

Carbon capture and sequestration (CCS) is receiving interest as a means for reducing global warming. CCS technology consists of separating the CO_2 from large point sources, such as fossil fuel power plants, and storing it so that it is not introduced to the atmosphere. Carbon capture technologies have been established and utilized in the chemical industry, such as the ammonia and urea synthesis processes where the CO_2 is scrubbed out of the syngas that consists mostly of CO and H_2 initially and the CO is converted by the water gas shift reaction, $CO + H_2O = CO_2 + H_2$ followed by scrubbing the gas with a suitable solvent to absorb the CO_2 leaving a decarbonized syngas. In the case of an IGCC, this decarbonized gas can be combusted in the gas turbine. A chemical solvent such as an aqueous amine solution or a physical solvent such as Selexol™ may be utilized, depending on the pressure of the syngas. This "precombustion" carbon capture technology is discussed in more detail in Chapter 9. In the case of direct combustion such as in a coal-fired boiler or a natural gas-fired gas turbine where "postcombustion carbon capture" technology is utilized, scrubbing the flue gas with a suitable aqueous amine solution (proven on natural gas-fired combined cycle) may be employed as discussed in more detail in Chapter 8. Both overall (energy) efficiency and capital cost are compromised significantly however, when these commercially available technologies are utilized for carbon capture and considerable research funds are being expended to develop technologies that reduce these penalties.

Technically, the major challenge in CCS is not the capture of the CO_2; it is the storage of the captured CO_2 for sequestration. The various proposals for sequestration include storage in depleted oil or gas wells, unminable coal beds, and deep saline aquifers. The U.S. National Energy Technology Laboratory has reported that there is enough storage capacity in North America to sequester CO_2 generated over the next 900 years at its current generation rate but the real concern is the geologic stability and the associated risk that the CO_2 might leak into the atmosphere. Research is underway to investigate the mineralization of the CO_2 by reactions with reservoir rocks that would be a long-term solution.

Deep ocean storage had been proposed but is no longer being considered due to the accompanying increase in acidity of the water. Using the CO_2 for enhanced oil recovery is another venue that can actually generate a positive revenue stream but such oil fields are limited. The CO_2 serves the purpose of pressurizing the oil field and reducing the viscosity of the petroleum to make it more free flowing by going into solution with the petroleum.

A large-scale CCS demonstration project has been operated since September 2000 in Canada. In this project, CO_2 separated from syngas generated in a gasification facility in the United States at 95% purity is transported via pipeline and injected into the Weyburn oil field in Saskatchewan at a rate of about 6500 tonnes/day CO_2.

1.2.3 Water Usage

Another environmental concern is the large amount of water used for heat rejection in today's power plants that utilize steam as the working fluid (in the Rankine cycle discussed in more detail in later chapters). Such power plants utilize a heat engine to convert heat to power and the conversion efficiency is far less than 100% due to limitations imposed by nature (and annunciated by the second law of thermodynamics discussed in Chapter 2) in converting a highly disorganized form of energy, the thermal energy, into a highly organized form of energy, the mechanical energy in the rotating shaft of the heat engine. In 2012, the water withdrawal/use in the United States was as much as 1300–1400 gal/person/day or 4.9–5.3 m^3/person/day (which includes industry, agriculture, and domestic uses) and more than half of this was used in power generation. The amount of water used by the power industry has an inverse relationship to plant efficiency when wet cooling towers are employed, which underscores the importance of power plant efficiency. Wet cooling towers provide cooling of the cooling water that is utilized for absorbing the heat rejected by the plant so that the cooling water may be recirculated for cooling. The cooling process, however, depends upon evaporating a portion of the cooling water (the latent heat of evaporation provides the cooling) by contacting the cooling water with ambient air, and this evaporated water is lost to the atmosphere. There are alternatives for wet cooling towers as discussed in the following, but some compromise efficiency and/or plant cost while others are currently under development.

Once-through systems take water from nearby sources such as rivers, lakes, and the ocean after some initial treatment and circulate the water to absorb the heat rejected by the plant. The water thus heated up is then returned to its source while taking precautions not to recirculate the warm returned water, that is, avoid the discharge to the intake. This type of cooling was initially the most popular because of its simplicity and low cost as long as the plant could be sited in close proximity to the source of water. The drawback with this type of cooling is the disruption caused to local ecosystems from the large rates of water withdrawals and returning of warmer water. Some plants employ a combination of wet cooling towers and this once-through cooling system to reduce the impact on the local ecosystem, but this scheme again has the disadvantage of water loss through evaporation in the wet cooling towers.

Dry-cooling systems use air instead of water to absorb the heat rejected by the plant and have been commercially employed. The major compromise with this type of cooling in a power plant is that the heat rejection temperature is typically increased due to the poorer heat transfer coefficient of air as compared to liquid water, requiring larger temperature driving forces within the heat exchanger to limit its size.

As explained in Chapter 2, the increase in the heat rejection temperature results in a reduction in the power cycle efficiency. The other drawback is that the plant cost is increased primarily due to the requirement for a very large (air cooled) exchanger.

A more recently developed cooling system technology called the "Green Chiller" technology is aimed at reducing the water usage as is the case with an air-cooled exchanger but without the accompanying compromise in plant efficiency. It also utilizes air as the cooling agent except that during warm days, the air is precooled by direct contact with water. In this precooled mode of operation, a portion of the water evaporates into the directly contacted air stream under adiabatic conditions and the latent heat required for the evaporation is taken from the air, thereby cooling the air. In this mode of operation, water is required for the cooling operation but the annual average water use of the plant is reduced when compared to a wet cooling tower-based system.

1.3 HOLISTIC APPROACH

In addition to practicing the environmental control strategies as discussed in previous sections at the generation point of the energy supply chain, improvements made at the raw materials supply side as well as at the end user side can greatly improve the sustainability of our planet.

1.3.1 Supply Chain and Life Cycle Assessment

Consider for example the drilling for shale gas. There are various environmental concerns due to not only the use of the large amount of water but also due to the various chemicals added to the water. There is concern over the migration of fracture fluids to aquifers and surface spills of undiluted chemicals. Measuring and disclosing operations and environmental data, engaging with local communities, surveying of the well sites to minimize their impacts, implementing robust designs in the construction of the wells, properly managing water usage and disposal, and providing appropriate resources to handle permitting and compliance are all essential to increasing the sustainability of such operations. There is also concern over the migration of gas through unplugged abandoned oil and gas wells as well as water wells (risk of house explosions and gas contamination of water wells). CH_4 is a potent greenhouse gas, much more potent than CO_2. Howarth et al. (2011), based on their comparison of total greenhouse gas emissions from shale gas that includes fugitive CH_4 emissions and coal, argue that shale gas has significantly higher greenhouse gas emissions than coal for the 20-year time horizon. This conclusion, however, is based on energy released by combustion as if thermal energy were the end product and does not necessarily apply when the end product is electrical energy because natural gas-fired power plants have a significantly higher overall efficiency than coal-fired plants, but nevertheless such fugitive emissions should be minimized. Coal-fired plants themselves have major challenges at the supply side, in the coal-mining operations. Coal-mining operations can result in diminishing the utility of land and if the land is left barren, then there is potential for erosion and landslides. Health and safety of the miners is also a major concern, especially when the mine owners do not provide safe working conditions and adequate equipment. In addition to the environmental impact of drilling or mining for the energy resource such as natural gas, oil, or coal, the processing of the resource before the resource is utilized for energy recovery as was described previously in this chapter should be taken into account with respect to its environmental impact. Inclusion of sustainability concepts in the original design of the operation as well as in ongoing operations is essential. A life cycle assessment starting from the acquisition of the raw materials to producing the end product as well as disposal of the used end product is absolutely necessary in identifying areas where improvements should be made, and in identifying which of the options is more sustainable on a cradle to grave basis. Purely an economic sustainability analysis, that is, one in which a monetary value to the environmental impact is not assigned, is not sufficient.

Higher efficiency processes led to the conservation of resources as well as reduction of the environmental impact. Energy efficiency has the potential to be a vast and low-cost “energy resource” for our planet both at the current time and in the future and to achieve this we need a coordinated international strategy to bring into practice existing high efficiency technologies, and continue research and development activities to make improvements in such technologies. There is potential for significant increase in efficiency at both the generation side as well as at the end user side. The emphasis in the following chapters is energy efficiency on the generation side but the importance of efficiency at the end user side should not be ignored. Changing end user habits is one aspect of increasing the overall system (inclusive of generation, transmission, and usage of electricity) efficiency and another is from a technological standpoint. As an example, consider the light bulb. Compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs) offer similar levels of performance as the incandescent lamps but use a fraction of the energy. Specifically, a study conducted by the U.S. Department of Energy found that energy-in-use of the life cycle is the dominant environmental impact, with 15-W CFL and 12.5-W LED lamps performing better than the 60-W incandescent lamp, all producing approximately the same light output.

The U.S. Department of Energy study on lighting also addressed the sustainability of the manufacture and disposal of the CFLs and LEDs. The presence of Hg in CFLs requires strict controls over their recycling, although relatively little is known about the full environmental impact of manufacturing and disposing of LEDs. Based on the data available, it was found that both CFLs and LEDs were far superior to incandescent lamps in this life cycle assessment with a slight advantage for LEDs over CFLs.

Thus, a life cycle assessment to include an assessment of the impact on the resources and the environment is required to get the complete picture. In a life cycle assessment, the air-related environmental impacts can include the potential for global warming, acidification, photochemical oxidation, stratospheric O_3 depletion, and human toxicity. Water-related environmental impacts can include potential for freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and eutrophication (e.g., increase of phytoplankton due to increased levels of nutrients causing depletion of O_2 in the water for aquatic life). Soil-related environmental impacts include land use, ecosystem damage potential, and terrestrial ecotoxicity. Resource-related environmental impacts can include abiotic (nonbiological such as inorganic salts, mineral soil particles) resource depletion, nonhazardous waste landfill, radioactive waste landfill, and hazardous waste landfill.

Going back to the example of lighting, in recent years the replacement of the incandescent lamps in homes and businesses with alternative CFL and LED-based products has been accelerated due to increased legislation banning the production of the incandescent light sources, stressing the important role that governments can play for the sustainability of the planet. Public awareness and acceptance of this type of lighting is equally important in a free society.

1.4 CONCLUSIONS

Processes that use less energy and resources are necessary for the long-term sustainability. It is sometimes argued that sustainable designs tend to be more complex and riskier requiring unproven technology and often greater capital expenditure but any risks and increases in capital expenditure should be compared to the indirect costs incurred by society on the long run due to disruption of the environment and the associated adverse health effects, and depletion of the finite natural resources.

There are both external and internal costs brought about by the finiteness of the earth's capacity to withstand the environmental impacts. External costs are associated with environmental disruptions on society but are not reflected by the monetary values assigned to energy. Internal costs are costs due to measures such as pollution control equipment to reduce the external costs. External costs have been rising despite a substantial increase in the internal costs. The external costs are difficult to quantify but civilization depends heavily on regulating water supply, controlling pests and pathogens, and maintaining a tolerable climate. Climate governs most of the environmental processes on which our well-being depends and global climatic changes brought about by greenhouse gases could be devastating. The CO_2 problem may be postponed by switching to natural gas, which buys us some time. Nuclear energy is less disruptive on the climate but requires development of much safer reactors and management of nuclear wastes. Solar energy is clearly the long-term solution from a standpoint of minimizing the external costs but at the present time remains expensive. The near-term solution is to transition into low-impact energy supply technologies (without disrupting economic growth) and increase end use efficiency. If the energy use in the developing countries increases to near that of the developed countries per capita, CO_2 and other pollutants would affect both locally and globally on a scale much larger than ever experienced. International cooperation in energy research in the areas of long-term alternatives is crucial.

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