Solutions Manual for

Sustainable Engineering

Concepts, Design, and Case Studies

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Chapter 1. An Introduction to Sustainability

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1. The IPAT Equation

Use the IPAT equation to estimate the percentage increase in the amount of energy that would be required, worldwide, in 2050, relative to 2006. To estimate the increase in population and affluence (the P and A in the IPAT equation), assume that population grows 1% per year and that global economic activity per person grows 2% per year. Assume that the energy consumption per dollar of GDP (the T in the IPAT equation) remains at 2006 levels. How much does this estimate change if population growth is 2% and economic growth is 4%?

Solution:

$I_{2006} = P_{2006}\ A_{2006}\ T_{2006}$

At 1% population growth per year and 2% per capita economic growth for 44 years:

$I_{2006}/I_{2006} = (P_{2006}/P_{2006})\ (A_{2006}/A_{2006})\ (T_{2006}/T_{2006}) = (1.01)^{44}(1.02)^{44}(1) = 3.7$

At 2% population growth per year and 4% per capita economic growth for 44 years:

$I_{2006}/I_{2006} = (P_{2006}/P_{2006})\ (A_{2006}/A_{2006})\ (T_{2006}/T_{2006}) = (1.02)^{44}(1.04)^{44}(1) = 13.4$

2. Affluence and energy use

Estimate the amount of energy that will be used annually, worldwide, if over the next 50 years world population grows to 10 billion and energy use per capita increases to the current per capita consumption rate in the US. What percentage increase does this represent over current global energy use?

Solution:

10 billion people * 330 million BTU/person/yr (from Example Problem 1.3-1) = 3300 Quadrillion BTU

This is roughly 7 times the current world energy consumption of 450-500 Quads

3. Energy efficiency in automobiles

Assume that the conversion of energy into mechanical work (at the wheel) in an internal combustion engine is 20%. Calculate gallons of gasoline required to deliver 30 horsepower at the wheel, for one hour.

Solution:

1 HP = 746 Watts

1 HP for 1 hour is 0.746 kWh

0.746 kWh * 3412 BTU/kWh = 2545 BTU

2545 BTU * 1 gal gasoline/124000 BTU * 1/0.2 = 0.1 gal

4. Water use by automobiles
Assuming that generating a kilowatt hour of electricity requires an average of 13 gallons of water (Example 1.4-3) and that an average electric vehicle requires 0.3 kWh/mi traveled (Kintner-Meyer, et. al., 2007), calculate the water use per mile traveled for an electric vehicle. If gasoline production requires approximately 10 gallons of water per gallon produced and an average gasoline powered vehicle has a fuel efficiency of 25 miles per gallon, calculate the water use per mile traveled of a gasoline powered vehicle.

<u>Solution:</u>
Water use per mile (electric vehicle) = 0.3 kWhr/mi * 13 gal/kWh = 4 gal/mi
Water use per mile (gas vehicle) = 10 gal water/gal gasoline * 1 gal gasoline/25 mi = 0.4 gal/mi

5. Energy efficiency in lighting
Assume that a 25 watt fluorescent bulb provides the same illumination as a 100 watt incandescent bulb. Calculate the mass of coal that would be required, over the 8000 hour life of the fluorescent bulb, to generate the additional electricity required for an incandescent bulb. Assume transmission losses of 10%, and 40% efficiency of electricity generation, and 10,000 BTU/lb for the heat of combustion of coal.

<u>Solution:</u>
The additional electricity required by the incandescent bulb is 75 watts over 8000 hours or 600 kWh. At 3412 BTU per kWh this is $2.05 * 10^6$ BTU. To generate this much electricity we need:

BTU primary fuel = $2.05 * 10^6$ BTU/((1-.1)(.4)) = $5.7 * 10^6$ BTU

$5.7 * 10^6$ BTU/(10,000 BTU/lb coal) = 570 lb coal

6. Energy Savings Potential of Compact Fluorescent versus Incandescent Light Bulbs
Compact fluorescent light bulbs provide similar lighting characteristics as incandescent bulbs, yet use just ¼ of the energy as incandescent bulbs. Estimate the energy savings potential on a national scale of replacing all incandescent bulbs in home (residential) lighting applications with compact fluorescent bulbs. In 2008, total U.S. energy consumption was 99.3 quadrillion (10^{15}) BTUs (quad) and electricity in all applications consumed 40.1 quads of **primary** energy. Assume that residential lighting is 3% of all electricity consumption in the U.S. and that all energy consumption for residential lighting is due to incandescent bulb use. How large (%) is the energy savings compared to annual U.S. energy consumption (2008 reference year)? Is this savings significant?

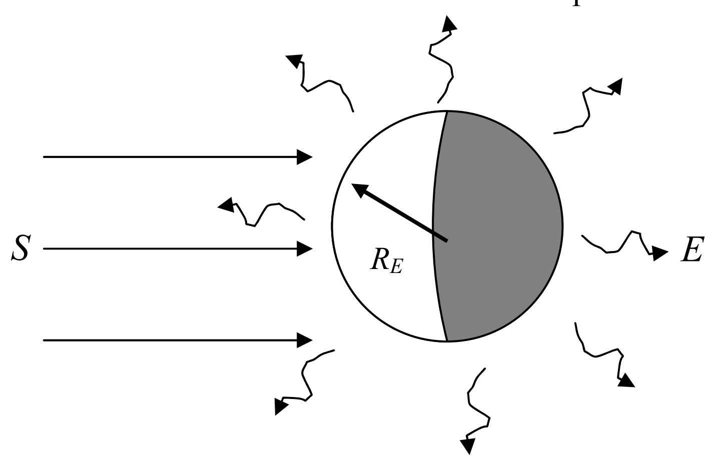
<u>Solution:</u>
Assuming incandescent bulb provide current residential lighting,
Current Primary Energy for Residential Lighting = (.03)(40.1 quads) = 1.2 quads

If fluorescent bulbs provided this residential lighting, primary energy consumed would be (1.2 quads)(¼) = 0.3 quads

Savings of primary energy is 1.2 – 0.3 = 0.9 quads, or 0.9/99.3 = 0.0091 (0.91%)

Is this savings significant? Yes, with a single change about 1% of energy can be saved. If several other energy saving steps could be found and implemented (insulation in residential homes, efficient lighting in commercial buildings, higher mileage vehicles, etc.), much larger savings could be found. The acceptability of any changes would have to be judged from a consumer standpoint based on economic factors and ease of adoption.

7. Global Energy Balance: No Atmosphere (adapted from Wallace and Hobbs, 1977)
The figure below is a schematic diagram of the earth in radiative equilibrium with its surroundings assuming no atmosphere. Radiative equilibrium requires that the rate of radiant (solar) energy absorbed by the surface must equal the rate of radiant energy emitted (infrared). Let S be the incident solar irradiance (1,360 Watts/meter^2), E the infrared planetary irradiance (Watts/meter^2), R_E the radius of the earth (meters), and A the planetary albedo (0.3). The albedo is the fraction of total incident solar radiation reflected back into space without being absorbed.



a) Write the steady-state energy balance equation assuming radiative equilibrium as stated above. Solve for the infrared irradiance, E, and show that it's value is 238 W/m^2.

Solution:
Energy Balance:
"Rate of Solar Energy Absorbed" = "Rate of Infrared Energy Emitted"

$$(1\text{-}A)\, S\, \pi\, R_E^2 = E\, 4\, \pi\, R_E^2$$

$$E = \frac{(1-A)S}{4} = \frac{(1-.3)(1{,}360\,\text{Watts}/m^2)}{4} = 238\ \text{Watts}/m^2$$

b) Solve for the global average surface temperature (K) assuming that the surface emits infrared radiation as a black body. In this case, the Stefan-Boltzman Law for a blackbody is $E = \sigma T^4$, σ is the Stefan-Boltzman Constant (5.67x10^{-8} Watts/(m^2•˚K^4)), and T is absolute temperature (˚K).

Compare this temperature with the observed global average surface temperature of 280 K. Discuss possible reasons for the difference.

Solution:
Global Average Surface Temperature:

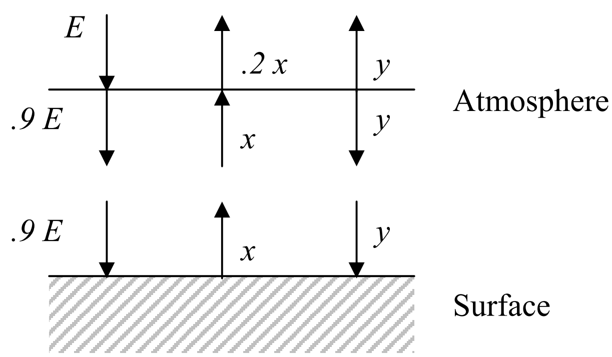
$$E = \sigma T^4$$

$$T = \left[\frac{E}{\sigma}\right]^{1/4} = \left[\frac{238\,\text{Watts / m}^2}{5.67 \times 10^{-8}\ \text{Watts / (m}^2 \bullet \text{K}^4)}\right]^{1/4} = 254.5\text{K}$$

Compared to 280 K, the actual average surface temperature. The calculated value is low because of the greenhouse effect was omitted.

8. Global Energy Balance: with a Greenhouse Gas Atmosphere (adapted from Wallace and Hobbs, 1977)

Refer to the schematic diagram below for energy balance calculations on the atmosphere and surface of the earth. Assume that the atmosphere can be regarded as a thin layer with an absorbtivity of 0.1 for solar radiation and 0.8 for infrared radiation. Assume that the earth surface radiates as a blackbody (absorbtivity = emissivity = 1.0).



Let x equal the irradiance (W/m^2) of the earth surface and y the irradiance (both upward and downward) of the atmosphere. E is the irradiance entering the earth-atmosphere system from space averaged over the globe (E = 238 W/m^2 from problem 2). At the earth's surface, a radiation balance requires that

$0.9E + y = x$
(irradiance in = irradiance out)

while for the atmosphere layer, the radiation balance is

$E + x = 0.9E + 2y + .2x$

a) Solve these equations simultaneously for y and x.
Solution:
At the earth's surface, a radiation balance requires that
(irradiance in = irradiance out)

$$0.9E + y = x$$

while for the atmosphere layer, the radiation balance is

$$E + x = 0.9E + 2y + .2x$$

Solving these equations simultaneously for y and x results in

$$y = \frac{.82}{1.2}E = \frac{.82}{1.2}(238\,W/m^2) = 162.6\,W/m^2$$

$$x = 1.583\,E = 1.583(238\,W/m^2) = 376.8\,W/m^2$$

b) Use the Stefan-Boltzman Law (see problem 2) to calculate the temperatures of both the surface and the atmosphere. Show that the surface temperature is higher than when no atmosphere is present (problem 2).

<u>Solution:</u>

Surface temperature:

$$x = 376.8\,W/m^2 = \sigma T^4$$

$$T = \left[\frac{x}{\sigma}\right]^{1/4} = \left[\frac{376.8\,W/m^2}{5.67\times10^{-8}\,W/(m^2 \bullet K^4)}\right]^{1/4} = 285.5\,K$$

Atmosphere temperature:

$$y = .8\,\sigma T^4$$

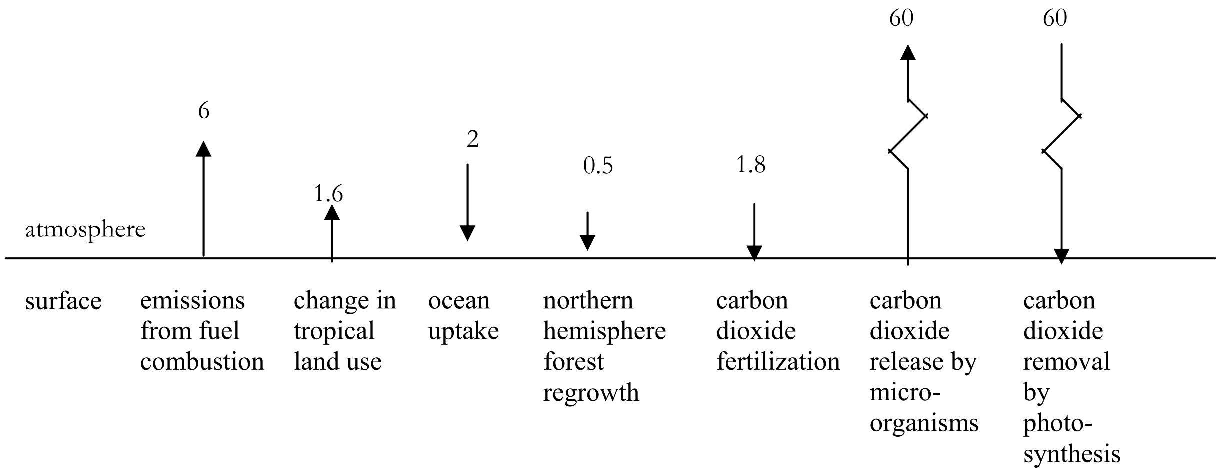
$$T = \left[\frac{y}{.8\sigma}\right]^{1/4} = \left[\frac{162.6\,W/m^2}{(.8)(5.67\times10^{-8}\,W/(m^2 \bullet K^4))}\right]^{1/4} = 244.7\,K$$

c) The emission into the atmosphere of infrared absorbing chemicals is a concern for global warming. Determine by how much the absorbtivity of the atmosphere for infrared radiation must increase in order to cause a rise in the global average temperature by 1˚C above the value calculated in part b.

<u>Solution:</u>

In order for the global average surface temperature of the earth to rise by 1 ˚C above the value calculated in part b (285.52K), the infrared absorbtivity would need to increase to 0.8166 from 0.80.

9. Global Carbon Dioxide Mass Balance
Recent estimates of carbon dioxide emission rates to and removal rates from the atmosphere result in the following schematic diagram (EIA, 1998a)



The numbers in the diagram have units of 10^9 metric tons of carbon per year, where a metric ton is equal to 1000 kg. To calculate the emission and removal rates for carbon dioxide, multiply each number by the ratio of molecular weights (44 g CO_2/12 g C).

a) Write a steady state mass balance for carbon dioxide in the atmosphere and calculate the rate of accumulation of CO_2 in the atmosphere in units of kg/yr. Is the accumulation rate positive or negative?

Solution:
A mass balance for CO_2 at the earth's surface is

Accumulation of CO_2 in atmosphere = rate of CO_2 release from surface - rate of CO_2 removal by surface

Accumulation of CO_2 in atmosphere (metric tons C/yr) = (60+6+1.6) - (60+2+.5+1.8)
= 3.3 metric tons C/yr

$$= \boxed{(3.3 \times 10^9 \text{ metric tons / yr})\left(\frac{44 \text{ gCO}_2}{12 \text{ gC}}\right)\left(\frac{10^3 \text{ kg}}{\text{metric ton}}\right) = +1.21 \times 10^{13} \text{ kgCO}_2 \text{ / yr}}$$

b) Change the emission rate due to fossil fuel combustion by +10% and recalculate the rate of accumulation of CO_2 in the atmosphere in units of kg/yr. Compare this to the change in the rate of accumulation of CO_2 in the atmosphere due to a +1% change in carbon dioxide release by micro-organisms.

Solution:
+10% change in emissions from fuel combustion is +.6% for a total of 6.6%

Accumulation of CO_2 in atmosphere (metric tons C/yr) = (60+6.6+1.6) - (60+2+.5+1.8)
= 3.9 metric tons C/yr

$$= \boxed{(3.9 \times 10^9 \text{ metric tons / yr})\left(\frac{44\,\text{g}CO_2}{12\,\text{gC}}\right)\left(\frac{10^3\text{ kg}}{\text{metric ton}}\right) = +\,1.43 \times 10^{13}\,\text{kg}CO_2\text{ / yr}}$$

+1% change in emissions from release by microorganisms is +.6% for a total of 60.6%

Accumulation of CO_2 in atmosphere (metric tons C/yr) = (60.6+6+1.6) - (60+2+.5+1.8)
= 3.9 metric tons C/yr

$$= \boxed{(3.9 \times 10^9 \text{ metric tons / yr})\left(\frac{44\,\text{g}CO_2}{12\,\text{gC}}\right)\left(\frac{10^3\text{ kg}}{\text{metric ton}}\right) = +\,1.43 \times 10^{13}\,\text{kg}CO_2\text{ / yr}}$$

c) Calculate the rate of change in CO_2 concentration in units of ppm per year, and compare this number with the observed rate of change stated in section 1.3.2. Recall the definition of parts per million (ppm), which for CO_2, is the mole fraction of CO_2 in the air. Assume that we are only considering the first 10 km in height of the atmosphere and that its gases are well mixed. Take for this calculation that the total moles of gas in the first 10 km of the atmosphere is approximately 1.5×10^{20} moles.

Solution:
Change in number of moles CO_2 from part a =

$$(1.21 \times 10^{13}\,\text{kg}CO_2\text{ / yr})\left(\frac{10^3\text{ g}}{\text{kg}}\right)\left(\frac{1\text{mole}CO_2}{44\,\text{g}CO_2}\right) = 2.75 \times 10^{14}\text{ moles}\,CO_2\text{ / yr}$$

Change in mole fraction (ppm) of CO_2 =

$$\boxed{\left(\frac{2.75 \times 10^{14}\text{ moles}CO_2\text{ / yr}}{1.5 \times 10^{20}\text{ moles air}}\right)\left(\frac{1\text{ppm}}{10^{-6}\,\frac{\text{moles}CO_2}{\text{moles air}}}\right) = 1.83\text{ppm / yr}}$$

This rate of change compares well with the observed rate of change of 0.5%/yr, which at the current concentration of CO_2 is (.005)(360 ppm) = 1.80 ppm/yr.

d) Describe how the rate of accumulation of CO_2 in the atmosphere, calculated in parts b and c, would change if processes such as carbon dioxide fertilization and forest growth increase as CO_2 concentrations increase. What processes releasing CO_2 might increase as atmospheric concentrations increase? (Hint: assume that temperature will rise as CO_2 concentrations rise).

Solution:
The rate of CO_2 accumulation would decrease if the processes of CO_2 fertilization and forest growth were enhanced by a future global temperature rise. On the other hand, the rate of CO_2 accumulation would increase if the processes of CO_2 release were accelerated, for example, by microbial metabolism in soil.

10. Electric Vehicles: Effects on Industrial Production of Fuels
Replacing automobiles having internal combustion engines with vehicles having electric motors is seen by some as the best solution to urban smog and tropospheric ozone. Write a short report (1-2 pages double spaced) on the likely effects of this transition on industrial production of fuels. Assume for this analysis that the amount of energy required per mile traveled is roughly the same for each kind of vehicle. Consider the environmental impacts of using different kinds of fuel for the electricity generation to satisfy the demand from electric vehicles. Background reading for this problem is found in "Industrial ecology and the automobile" by Thomas Graedel and Braden Allenby, Prentice Hall, 1998.

Solution:
There are two main points to be addressed by this question of electric vehicles versus conventional gasoline-powered vehicles: 1) what are the changes likely to occur in industrial fuels production, and 2) what are the likely changes in environmental impact as a result of this change due to combustion of these fuels. To address the first question, information is needed on the average mix of energy sources in the United States for electricity generation. According to the Department of Energy (DOE) in a report "GREET 1.5 – Transportation Fuel-Cycle Model" (http://www.transportation.anl.gov/ttrdc/greet/), the average mix is 53.8% coal, 1.0% oil, 14.9% natural gas, 18% nuclear, and 12.3% others (hydroelectric, wind, solar, etc.). Thus, if electric vehicles replace conventional gasoline-powered vehicles for personal transportation, fuels production and import would switch from petroleum and petroleum products to more coal, natural gas, nuclear, and other. There would be more mining activities for the extraction of coal and uranium and less reliance on foreign oil. The second question, regarding the environmental impacts of the combustion processes to supply the electricity, is more complicated. A study using the GREET model indicate that on a per mile traveled basis comparing electric vehicles compared to conventional gasoline-powered vehicles, CO_2 emissions would decrease by about 25%, volatile organic compounds (VOCs) and CO decrease by about 80%, NOx would increase by about 60%, and SO_2 would increase by about 240%.

11. Essay on an Environmental Issue
Read an article from a science or engineering journal, from a popular magazine, or from the internet on some environmental issue that is of interest to you. Summarize the article, in a short Memorandum format, addressed to your instructor. In the body of the Memorandum, limit the length to **one page** of single-spaced text including graphics/tables (if needed). Structure the Memorandum as

i. introduction and motivation,
ii. a description of the issue, and
iii. a description of what engineers are doing, have done, or are going to do to address the challenge.

Use of headings is appropriate and be sure to reference information sources.

Potential Topics

a) Stratospheric Ozone Depletion: the chemical industry connection

b) Smog in Industrialized Urban Areas
c) Toxic Chemicals in Commerce and in the Environment
d) Industrial Hazardous Waste Generation and Management
e) Environmental Challenges for Genetically-Engineered Foods
f) The Clean Up of Industrial Sites (Superfund Program)
g) Pollution Prevention Issues, Technologies, or Initiatives
h) Endocrine disruptors: what are they, why are they harmful, and what is the chemical industry doing about them?
i) Environmental effects (advantages / disadvantages) of biodiesel or corn/cellulosic ethanol for transportation fuels
j) Fuel cells and their environmental consequences
k) Water resources: quality and quantity
l) Petroleum: are we running out? What are the alternatives?
m) Renewable energy: what are they and can they make a difference?

Potential Sources of Information
Scientific and Engineering Research Journals (check the library current journals section)
1. Environmental Science and Technology
2. Environmental Progress and Sustainable Energy
3. Industrial and Engineering Chemistry Research
4. Chemical and Engineering News
5. Science
6. Scientific American

Internet Resources
1. American Chemistry Council (formerly the Chemical Manufacturers Association)
2. US Environmental Protection Agency (http://www.epa.gov)
3. Your state's Department of Environmental Quality

Solution:
Instructor should read the student's written work and grade according to a chosen rubric

12. Sustainable Development
An overview of the Report on the World Commission on Environment and Development is at http://www.un-documents.net/ocf-ov.htm. A number of global challenges on the environment, economic development, and living conditions were discussed. Summarize one or two of the key challenges in a memo format in 1-2 pages.

Solution:
Instructor should read the student's written work and grade according to a chosen rubric

13. International Trade in Waste
One of the consequences of the globalization of trade is a growing global trade in waste, often toxic and hazardous waste. Read a recent article on this subject and write a 1-2 page memo on

key findings. Include a reference or references on your memo. One possible source of information is the International Network for Environmental Compliance and Enforcement (http://www.inece.org/seaport/SeaportWorkingPaper_24November.pdf).

Solution:
Instructor should read the student's written work and grade according to a chosen rubric

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Chapter 2. Risk and Life Cycle Frameworks for Sustainability

1. **Voluntary risk**
   Each year, approximately 45,000 persons lose their lives in automobile accidents in the United States (population 281 million according to the 2000 census). How many fatalities would be expected over a three-day weekend in the Minneapolis-St. Paul, Minnesota metropolitan area (population 2 million)?

Solution:

$$45{,}000 \text{ Deaths} = (281\times 10^{6} \text{ people})(1 \text{ year}) \times (\text{Hazard})$$

Solving for Hazard we calculate,

$$\text{Hazard} = \frac{45{,}000 \text{ Deaths}}{(281\times 10^{6} \text{ People})(1 \text{ year})} = 1.61\times 10^{-4}\ \frac{\text{Deaths}}{\text{No. People} \bullet \text{year}}$$

The number of deaths expected in Minneapolis-St. Paul over a three-day weekend is

$$\boxed{\text{Risk} = (2\times 10^{6} \text{ People})\left(\frac{3 \text{ days}}{365 \text{ days / yr}}\right) \times \left(1.61\times 10^{-4}\frac{\text{Deaths}}{\text{No. People} \bullet \text{yr}}\right) = 2.63 \text{ deaths}}$$

2. **Involuntary risk**
   Lurmann, et al. (1999) have estimated the costs associated with ozone and fine particulate matter concentrations above the National Ambient Air Quality Standards (NAAQSs) in Houston. They estimated that the economic impacts of early mortality and morbidity associated with elevated fine particulate matter concentrations (above the NAAQS) are approximately $3 billion/year. Hall, et al. (1992), performed a similar assessment for Los Angeles. In the Houston study, Lurmann et al examined the exposures and health costs associated with a variety of emission scenarios. One set of calculations demonstrated that a decrease of approximately 300 tons/day of fine particulate matter emissions resulted in a 7 million person-day decrease in exposure to particulate matter concentrations above the proposed NAAQS for fine particulate matter, 17 less early deaths per year, and 24 fewer cases of chronic bronchitis per year. Using estimated costs of $300,000 per case of chronic bronchitis and $7,000,000 per early death, estimate the social cost per ton of fine particulate matter emitted.

Solution:
Reduction: 300 tons/day of fine particulate matter
Expected Benefits: 17 less early deaths/yr, and 24 fewer cases of chronic bronchitis per year
Costs: $7,000,000 per early death and $300,000 per case of chronic bronchitis.

Net Cost Reduction = (17 less early deaths/yr)(\$7,000,000 per early death) + (24 chronic bronchitis cases per year)(\$300,000 per case of chronic bronchitis) = \$126x10^6/yr.

Social Costs Per Ton Emitted: (\$126x10^6/yr)/[(300 tons/day)(365 days/yr)] = **\$1150/ton**.

In Table 3-27 of the American Institute of Chemical Engineers' Center for Waste Reduction Technologies Total Cost Assessment Methodology, July 22, 1999, a range of health costs of cancer was shown to span the range of \$2/ton to tens of millions of dollars/ton of pollutant emitted to the air. The value calculated in this problem is within that very broad range.

3. Life cycles of cups

In evaluating the energy implications of the choice between reusable and single use cups, the energy required in heating wash water is a key parameter. Consider a comparison between single-use polypropylene (PP) and reusable PP cups. The reusable cup has a mass roughly 14 times the single use cup (45 g vs 3.2 g), which, in turn requires petroleum feedstocks.

a.) Calculate the number of times the reusable cup must be used in order to recoup the energy in the petroleum required to make the reusable cup

b.) Assuming that the reusable cup is washed after each use in 0.27 liters of water, and that the wash water is 80°C (heated from 20°C), calculate the energy used in each wash if the water is heated in a gas water heater with an 80% efficiency. Calculate the number of times the reusable cup must be used in order to recoup both the energy required to make the reusable cup and the energy used to heat the wash water. Assume that 1.2 kg of petroleum is required to produce 1 kg of polypropylene and that the energy of combustion of petroleum is 44 MJ/kg.

c.) Repeat part b.) assuming that an electric water heater is used (80% efficiency) and that electricity is generated at from fuel at a 33% efficiency

$$C_p \text{ of water} = 4.184 \text{ J/g K}$$

Solution:

a.) Since both the single use and the disposable cup are made of the same material, the energy use used to manufacture the cup will scale with the mass of the cups. Reusable cup must be used 14 times (45/3.2) to recoup the energy in the petroleum used to make the reusable cup

b.) energy used per wash = 4.184 J/g K * 60°K * 270 g water * 1/0.8 = 0.085 MJ
Energy used per disposable cup = .0032 kg *1.2 *44 MJ/kg = 0.169 MJ
Energy used per reusable cup = .045 * 1.2 * 44 MJ/kg = 2.38 MJ
Energy is equal when 2.38 + .085 n = .169 n   n = 28 uses

c.) Energy used per wash increases by a factor of 3 to 0.255 MJ; since this is more than the energy used per disposable cup, the reusable cup is never the preferable choice

4. Durability versus efficiency improvements in newer products

In minimizing the environmental footprints of products, there is a tension between product durability and rapidly replacing older products with newer products that have less environmental impact associated with their use. Consider the question – when is it most energy efficient to replace my vehicle?

a. The production of a 1995 vehicle consumed 125,000 MJ of energy, and that the energy intensity of the materials used in manufacturing automobiles (energy required per kg of material) decreases by 1-2% per year. Assuming that the energy intensity of automobile manufacturing decreased by 1.5% per year between 1990 and 2020, calculate the energy required to produce a new automobile during the model years 1990, 2005, and 2010.

b. The projected average fuel economy of light duty automobiles is expected to increase from 27.5 to 32.5 mi/gal between 1990 and 2020. Assume that this increase occurs in step changes, with an average fuel economy of 27.5 mpg between 1990 and 1999, 30 mpg between 2000 and 2009, and 32.5 mpg between 2010 and 2019. Calculate the amount of energy used (assuming an energy content for gasoline of 124,000 BTU per gal, $1.3 * 10^8$ J/gal) for vehicles travelling 12 thousand miles per year for the decades of the 1990s, 2000s, and 2010s.

c. Is it more efficient to replace a vehicle every 10 years or every 15 years?

Solution:

a.) 1990: 125,000 MJ$*(1.015)^5$ = 135,000 MJ
2000: 125,000 MJ $* (1.015)^{-5}$ = 116,000 MJ
2005: 125,000 MJ $* (1.015)^{-10}$ = 108,000 MJ
2010: 125,000 MJ $* (1.015)^{-15}$ = 100,000 MJ
2020: 125,000 MJ $* (1.015)^{-25}$ = 86,000 MJ

b.) 1990s: 12,000 miles/yr * 1 gal/27.5 miles * $1.3 * 10^8$ J/gal = 57,000 MJ/yr

2000s: 12,000 miles/yr * 1 gal/30 miles * $1.3 * 10^8$ J/gal = 52,000 MJ/yr

2010s: 12,000 miles/yr * 1 gal/32.5 miles * $1.3 * 10^8$ J/gal = 48,000 MJ/yr

c.) Scenario 1: new car purchases in 1990, 2000 and 2010 and gas use at 570,000 MJ for car 1 + 520,000 for car 2 + 480,000 for car 3 = 135,000 +116,000 +100,000 +570,000 + 520,000 + 480,000 = 1921 GJ

Scenario 2: new car purchases in 1990 and 2005 and gas use of 15 * 57,000 for car 1 and 15 * 52,000 for car 2 = 135,000 + 108,000 + 855,000 + 780,000 = 1878 GJ

The more energy efficient strategy is to change cars every 15 years.

5. **Options for moving energy**

Approximately1 billion tons of coal are burned annually in the United States, providing 50% of the country's electricity consumption. The coal may either be moved by train from the mine to power plants near where the power is used, or the coal could be combusted near the mine mouth to generate electricity and the electricity could be transmitted over long distances to the users. As a case study of this trade-off, consider electricity use in Dallas, which is generated, in part, using coal from the Powder River Basin (PRB) in Wyoming. Power plants using PRB coal supply 6.5 billion kilowatt hours of power per year to the Dallas area, at an average conversion efficiency (energy in the generated electricity per energy in the fuel burned) of 33%. The coal mined at the PRB has a heat content of 8340 Btu/lb coal. coal (1 kWhr = 3412 BTU)

a. Determine the amount of coal required from the PRB to support consumers in Dallas.
b. If the energy required to transport coal by train is 0.0025 gallons per ton mile, and the distance from the PRB to Dallas is 1000 miles, calculate the amount of energy required to transport the coal to Texas, and the total energy consumed in combustion and transport. What fraction of the total energy is consumption is due to transport? Assume that diesel fuel has an energy content of 124,000 BTU/gal.
c. Calculate the amount of coal consumed if the electricity were generated at the mine (assume a 33% power plant efficiency) and if the transmission losses for the electricity, from the mine to Dallas were 7%.
d. Which option (transporting coal or transporting electricity would be more efficient?

Solution:

a.) 6.5 billion kW-hr * 3 kw-hr coal/1 kW-hr elec. * 3412 BTU/kWhr * 1 lb/8340 BTU = 8 billion lb or 4 million tons

b.) 4 million tons * 1000 mi * .0025 gal/ton mi * 124,000 BTU/gal = 1240 billion BTU 67,000 billion BTU is combustion energy of coal and 1240 billion BTU in transport or 2%

c.) 6.5 billion kWhr * 1.07 * 3 kw-hr coal/1 kW-hr elec. * 3412 BTU/kWhr * 1 lb/8340 BTU = 8.5 billion lb or 4.3 million tons (7% more)

d.) Transport by train is more energy efficient

6. Functional Unit in Life Cycle Assessment: Personal Mobility

Mobility is one of the measures of quality of life that citizens of many developed nations value highly, ranked behind only food and shelter as necessities for life. Mobility is also a key factor in sustainability because of cumulative effects of providing mobility on the environment, resource depletion, and on the economy.

In the table below, data are presented on two modes of transportation, automobiles and buses. Use these data to answer the questions to follow.

Annual Average Personal Transportation Data for the U.S. (http://www1.eere.energy.gov/vehiclesandfuels/facts/2010_fotw613.html)

Automobiles (cars)	27.5 miles per gallon gasoline (2010 CAFÉ std.) 1.6 persons per automobile
Buses	6 miles per gallon diesel (est.) 30 persons per bus (est.)

Other data and conversion Factors: 150,000 BTU/gallon gasoline*, 163,000 BTU/gallon diesel*

4.3+19.4 lb CO_2 equivalents/gallon gasoline (production + combust.)

3.6+22.2 lb CO_2 equivalents /gallon diesel (production + combust.)

* includes production energy and feedstock energy over the fuel life cycle.

a. Define an appropriate functional unit for a comparison of the bus and car transportation from Table 1 for personal mobility.

Solution:

As you consider functional units, recognize that the primary function of any mobility technology is to transport people over a distance. Secondary functions might include providing other benefits like freedom of movement, prestige, and image. An appropriate functional unit for mobility that addresses the primary function would be the number of people transported over a certain distance (**a person mile**). From this definition, an inventory of materials, energy, and emissions can be developed to satisfy this functional unit.

b. Calculate the gallons of fuel needed to satisfy the transportation functional unit, and then convert gallons to energy (BTUs per functional unit). Also, calculate the CO_2 emissions per functional unit (lb CO_2 emitted / functional unit).

Solution:

Automobile: (1 automobile/1.6 persons) / (27.5 miles/gallon gasoline/automobile) =

0.023 gallons/(person-mi); x (150,000 Btu/gallon) =

3,409 Btu/(person-mi)

(1 automobile/1.6 persons) / (27.5 miles/gallon gasoline/automobile) =

0.023 gallons/(person-mi); x (4.3+19.4 lb CO_2 equivalents/gallon) =

0.55 lb CO_2 equivalents /(person-mi)

Buses: (1 bus/30 persons) / (6 miles/gallon diesel/bus) =
0.0056 gallons/(person-mi); x (163,000 Btu/gallon) =
906 Btu/(person-mi)
(1 bus/30 persons) / (6 miles/gallon diesel/bus) =
0.0056 gallons/(person-mi); x (3.6+22.2 lb CO_2 equivalents/gallon) =
0.14 lb CO_2 equivalents /(person-mi)

c. Compare bus and auto transport based on energy consumption and greenhouse gas emissions.

<u>Solution:</u>
Energy: Bus transportation is (906/3,409) = 0.266 (26.6%) of automobile transportation
GHG: Bus transportation is (0.14/0.55) = 0.254 (25.4%) of automobile transportation

7. Functional Unit in Life Cycle Assessment: Transport of Goods
Transport of goods is another important energy consuming and greenhouse gas emitting activity and, as in personal mobility, there are choices in modes of freight transportation.

In the table below, data are presented on three modes of freight transportation; by road (heavy trucks), by rail, and by ship (oceanic freighter). Use these data to answer the questions to follow.

Annual Average Freight Transportation Data for the U.S.
(Transportation Energy Data Book, US Dept. of Energy, 2010)

Road (heavy truck)	1 gallon diesel transports 20 tons 5.5 miles
Rail	1 gallon diesel transports 1 ton 423 miles
Ship (oceanic freighter)	1 gallon heavy oil transports 1 ton 1,500 miles

Other data and conversion Factors: 190,000 BTU/gallon heavy oil, 163,000 BTU/gallon diesel
3.7+26.0 lb CO_2 e/gallon heavy oil (production + combust.)
3.6+22.2 lb CO_2 e /gallon diesel (production + combust.)

a. Define an appropriate functional unit for a comparison of the transportation modes shown in the table for freight transportation.

<u>Solution:</u>
The purpose of freight transportation is to carry a certain amount of goods over a distance, therefore an appropriate functional unit would be a **ton-mile**.

b. Calculate the gallons of fuel needed to satisfy the freight transportation functional unit, and then convert gallons to energy (BTUs per functional unit). Also, calculate the CO_2 emissions per functional unit (lb CO_2 emitted / functional unit).

<u>Solution:</u>
Road: (1 gallon diesel / 20 tons • 5.5 miles) = **0.0091 gallons / ton • mile;**
x (163,000 Btu/gallon) = **1,481 Btu / ton • mi**

(1 gallon diesel / 20 tons • 5.5 miles) = **0.0091 gallons / ton • mile;**
x (3.6+22.2 lb CO_2 equivalents/gallon) = **0.23 lb CO_2 equivalents / ton • mi**
Rail: (1 gallon diesel / 1 ton • 423 miles) = **0.0024 gallons / ton • mile;**
x (163,000 Btu/gallon) = **385 Btu / ton • mi**
(1 gallon diesel / 1 ton • 423 miles) = **0.0024 gallons / ton • mile;**
x (3.6+22.2 lb CO_2 equivalents/gallon) = **0.061 lb CO_2 equivalents / ton • mi**
Ship: (1 gallon heavy oil / 1 ton • 1,500 miles) = **0.00067 gallons / ton • mile;**
x (190,000 Btu/gallon) = **127 Btu / ton • mi**
(1 gallon diesel / 1 ton • 1,500 miles) = **0.00067 gallons / ton • mile;**
x (3.7+26 lb CO_2 equivalents/gallon) = **0.020 lb CO_2 equivalents / ton • mi**

c. Rank the transportation modes from the least energy and greenhouse gas intensive to the most energy and greenhouse gas intensive.

Solution:
Energy: **Ship < Rail < Road; (127 < 385 > 1,481 Btu / ton • mi)**
GHG: **Ship < Rail < Road; (.02 < .061 > .23 lb CO_2 equivalents / ton • mi)**

8. Transport of goods: Truck or air?
Use the US Life Cycle Inventory Database (www.nrel.gov/lci) to determine the relative amount of diesel fuel required to transport one ton of freight 1000 kilometers by truck and by air.

Solution:
As of September 2011, the US Life Cycle Inventory database had the following data posted:

For a combination truck using diesel fuel, the consumption of diesel fuel per tkm is 0.0272 L
Transporting one ton of freight 1000 km requires 27.2 L

For an aircraft using kerosene (roughly similar to diesel) fuel, the consumption of fuel per tkm is 0.42 L
Transporting one ton of freight 1000 km requires 420 L

9. Economic Input Output Life Cycle Assessment
Review the input-output model for life cycle assessment, developed by Carnegie Mellon University. This model is available at the web site www.eiolca.net. The model available at the site allows you to estimate the overall environmental impacts from expending a user defined dollar amount in any of roughly 400 economic sectors in the United States. It provides rough guidance on the relative impacts of different types of products, materials, services, or industries in the US, up to the point of purchase.

Use the model to answer these questions:

a. What is the most energy intensive sector of the chemical industry (measured as total life cycle energy use per million dollars of sales)?

b. What suppliers to the automotive sector have the greatest emissions of greenhouse gases?

c. How much energy is used to manufacture a passenger vehicle costing $20,000? How does this compare to the energy consumption due to driving the vehicle? Assume that the car is driven 200,000 miles and gets 30 miles per gallon of gasoline consumed. Assume that the gasoline has a heating value of 124,000 BTU per gallon and that it takes 10,000 BTU of energy to produce the gasoline.

Solution:
The precise numerical solution to these questions will depend on which set of industry data are used in the EIOLCA model, however, the general features of the solutions will remain consistent. This solution was obtained with the US 2002 Purchaser price model.

a. The energy intensity of the sectors of the US chemical industry (Resin, rubber, artificial fibers, agricultural chemicals and pharmaceuticals sector), by sector is:

Plastics:	42 TJ/million dollars
Rubber:	32 TJ/million dollars
Fibers:	28 TJ/million dollars
Fertilizers:	44 TJ/million dollars
Pesticides:	15 TJ/million dollars
Medicinals:	7 TJ/million dollars
Pharmaceuticals:	5 TJ/million dollars
Diagnostic chemicals:	5 TJ/million dollars
Biologicals:	5 TJ/million dollars

So, the most energy intensive sector is fertilizer manufacturing, followed closely by plastics manufacturing.

b. The greenhouse gas emissions from automobile manufacturing are captured in the screen shot shown:

Carnegie Mellon

eiolca.net

HOME >> USE THE TOOL >> BROWSE **US 2002 (428)** MODEL >> DISPLAYING...

Sector #336111: Automobile Manufacturing
Economic Activity: $1 Million Dollars
Displaying: Greenhouse Gases
Number of Sectors: Top 10

Change Inputs (Click here to view greenhouse gases, air pollutants, etc...)

Documentation:
The environmental, energy, and other data used and their sources.
Frequently asked questions about EIO-LCA.

This sector list was contributed by Green Design Institute.

	Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
	Total for all sectors	*563.*	*412.*	*81.4*	*41.9*	*13.0*	*14.5*
221100	Power generation and supply	180	177.0	0	0.488	1.10	1.14
331110	Iron and steel mills	108.0	40.7	66.5	0.657	0	0
484000	Truck transportation	24.1	24.1	0	0	0	0
211000	Oil and gas extraction	20.4	5.75	3.74	10.9	0	0
1121A0	Cattle ranching and farming	12.4	0.815	0	7.07	4.55	0
325190	Other basic organic chemical manufacturing	11.3	10.1	0	0	1.16	0
324110	Petroleum refineries	11.1	11.1	0	0.035	0	0
336300	Motor vehicle parts manufacturing	10.9	10.9	0	0	0	0
336111	Automobile Manufacturing	10.8	10.8	0	0	0	0
33131A	Alumina refining and primary aluminum production	10.7	2.42	3.79	0	0	4.46

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Electrical power generation and supply is the dominant source of greenhouse gas emissions in manufacturing an automobile.

c. A screen shot showing the energy required to manufacture a $20,000 automobile is 0.167 TJ.

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HOME >> USE THE TOOL >> BROWSE **US 2002 (428)** MODEL >> DISPLAYING...

Sector #336111: Automobile Manufacturing
Economic Activity: $0.02 Million Dollars
Displaying: Energy
Number of Sectors: Top 10

Change Inputs (Click here to view greenhouse gases, air pollutants, etc...)

Documentation:
The environmental, energy, and other data used and their sources.
Frequently asked questions about EIO-LCA.

This sector list was contributed by Green Design Institute.

	Sector	Total Energy TJ	Coal TJ	NatGas TJ	Petrol TJ	Bio/Waste TJ	NonFossElec TJ
	Total for all sectors	*0.167*	*0.051*	*0.053*	*0.026*	*0.009*	*0.028*
221100	Power generation and supply	0.044	0.032	0.009	0.002	0	0.001
331110	Iron and steel mills	0.025	0.015	0.007	0.000	0.000	0.003
336300	Motor vehicle parts manufacturing	0.009	0.000	0.004	0.000	0.000	0.005
336111	Automobile Manufacturing	0.008	0.000	0.004	0.000	0.000	0.003
484000	Truck transportation	0.007	0	0	0.006	0	0.000
325190	Other basic organic chemical manufacturing	0.005	0.000	0.002	0.000	0.002	0.000
324110	Petroleum refineries	0.004	0.000	0.001	0.002	0.000	0.000
33131A	Alumina refining and primary aluminum production	0.003	0	0.001	0.000	0.000	0.002
325211	Plastics material and resin manufacturing	0.003	0.000	0.002	0.000	0.000	0.000
322130	Paperboard Mills	0.003	0.000	0.000	0.000	0.002	0.000

Download View Graph

To drive a car 200,000 miles at 30 mpg requires 6667 gallons of gasoline. At 134,000 BTU gal this is 6667*134,000 = 894 * 10^6 BTU Since 1 BTY = 1055 J, this is 943 * 10^9 J or 0.943 TJ. Total energy consumption over the life of the vehicle is 0.943 + 0.167 = 1.11 TJ. Manufacturing the vehicle takes 15% of that energy (0.167 TJ is 15% of 1.11 TJ)

Chapter 3. Environmental Law and Regulations

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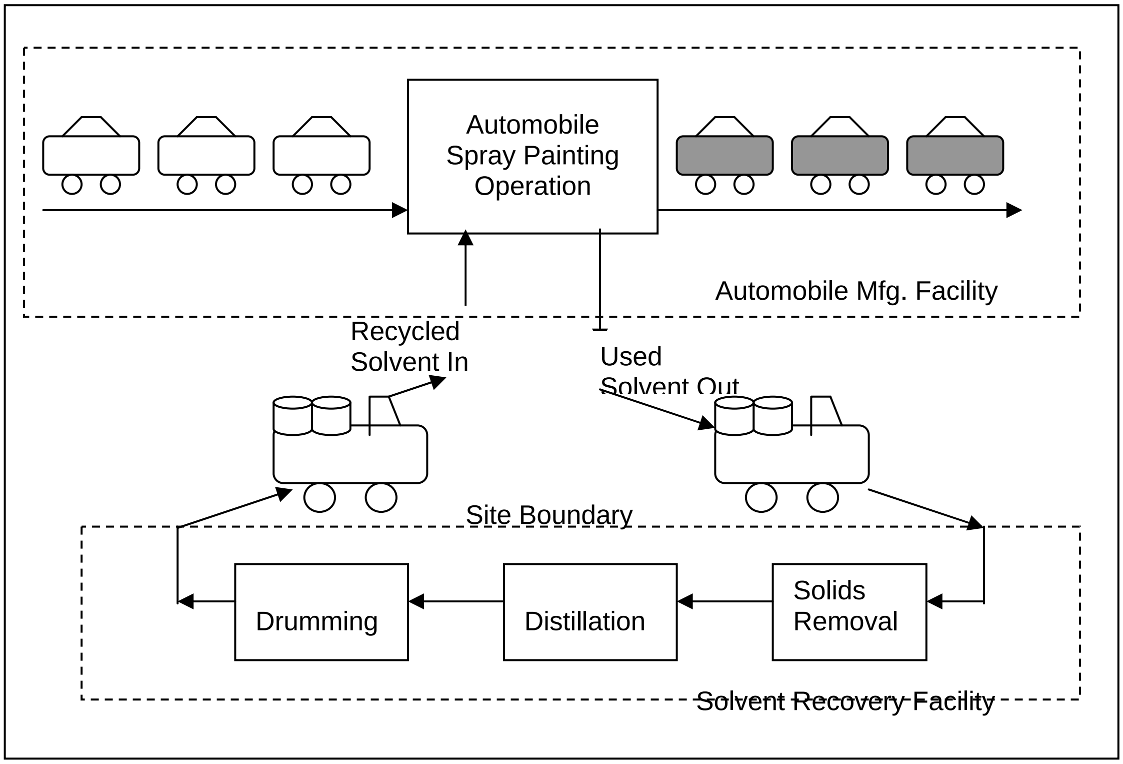
1. Terms and Definitions for Environmental Management
Provide definitions for the following terms

Solution:
a) pollution prevention: Any act of source reduction, in-process recycle, on-site recycle, and off-site recycle that reduces the amounts of releases and the hazardous characteristics of those releases which ultimately reach the environment.
b) source reduction: Any modification of a manufacturing process or of production procedures which reduces the amount of components entering a waste stream or the hazardous characteristics of those components entering waste streams prior to recycle, treatment, or disposal.
c) in-process versus on-site versus off-site recycle: In-process recycle is the recovery and return of components that would otherwise become waste to the process unit where these components were generated, usually immediately after they are generated. Examples would be unconverted reactants leaving a reactor that are separated and returned to the reactor inlet. On-site recycle is the recovery of valuable stream components using process units within the same facility where those components were generated. Off-site recycle is the recovery of valuable components at a remote location from waste streams generated at a facility and the return of the valuable components to the facility.
d) waste treatment: Any process that renders a waste stream less hazardous prior to disposal or direct release through physical, biological, or chemical means. Examples are primary, secondary, and tertiary wastewater treatment, adsorption of volatile organic compounds from air, and landtreatment of petroleum hydrocarbon sludges from tank bottoms.
e) disposal: Long-term isolation of raw or treated waste components in a secured landfill. Examples include landfills for domestic and industrial hazardous and non-hazardous waste.
f) direct release: The direct release of components from processes to the air, land, or water. An example of this includes the release of volatile organic compounds from fugitive emission sources in chemical or petroleum refinery processes (from valves, fittings, pumps, flanges, connectors, etc.).

2. Solvent Recovery Operation in the Automobile Industry
Categorize the following solvent recovery operation in terms of the waste management hierarchy. Discuss the pollution prevention features of this process. Assess whether this process is pollution prevention,.

Process Description: The automotive industry uses robots to paint automobile bodies before attaching them to the chassis, and installing other components such as the drive train, lights, trim, and upholstery. In order to accommodate different colors, the paint lines must be flushed with a solvent and then re-charged with the new color paint. In the past, this solvent and paint residue was disposed of as hazardous waste or incinerated. The current process of spray painting automobiles uses a closed-loop solvent recovery process as outlined in the diagram below (Gage Products, Ferndale, MI).



<u>Solution:</u>
This recycle operation is an example of off-site recycle. The location of the solvent recovery facility is remote from the locations of automobile manufacture. The feed for the solvent recovery facility is the waste streams from these cleaning processes in automobile assembly painting. This activity would be considered pollution prevention using the expanded definition in this text but would not be considered pollution prevention by the federal definition, which only includes source reduction and in-process recycle.

3. Analysis of Federal Environmental Statutes.
Choose one of the nine federal environmental statutes and then analyze the regulatory provisions for the potential to impact a chemical production facility's capital and operating costs. What are the key provisions requiring action? What is the nature of those actions? What are the cost implications of those actions? The information contained in the Appendix to this chapter will be helpful in answering these questions.

<u>Solution:</u>

a) *The Toxic Substances Control Act (TSCA) of 1976*
Chemical manufacturers must submit information on existing chemicals. This information includes chemical identity, name and molecular structure, categories of use, amounts manufactured or processed, byproducts from manufacture, processing, use, or disposal, environmental/health effects of chemical and byproducts, and exposure information. Companies