Solutions Manual for

# Sustainable Engineering

## Concepts, Design, and Case Studies

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ISBN-10: 0-13-275662-5
ISBN-13: 978-0-13-275662-4

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# Chapter 1. An Introduction to Sustainability

## 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?

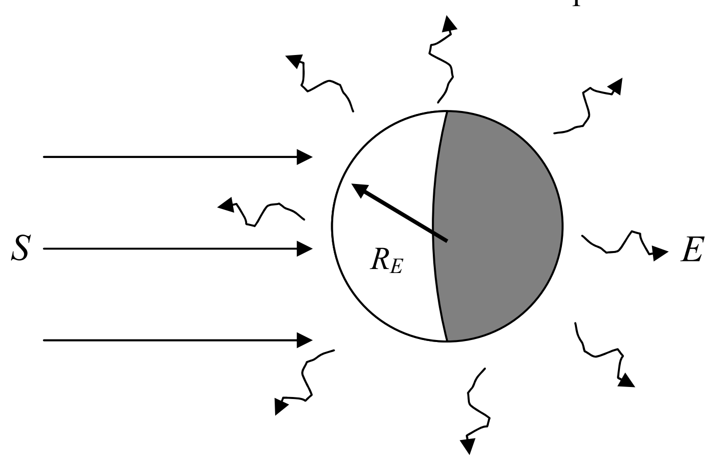
<u>Solution:</u>
Assuming incandescent bulb provide current residential lighting,
Current Primary Energy for Residential Lighting = (.03)(40.1 quads) = 1.2 quads

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 $E = \sigma T^4$, $\sigma$ 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:

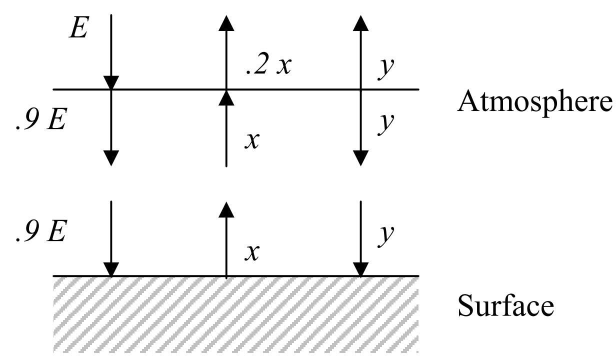
$$E = \sigma T^4$$

$$T = \left[\frac{E}{\sigma}\right]^{1/4} = \left[\frac{238\,\text{Watts}/\text{m}^2}{5.67\times10^{-8}\,\text{Watts}/(\text{m}^2\bullet\text{K}^4)}\right]^{1/4} = 254.5\text{K}$$

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).
Solution:
Surface temperature:

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

$$T = \left[\frac{x}{\sigma}\right]^{1/4} = \left[\frac{376.8\, W/m^2}{5.67 \times 10^{-8}\, W/(m^2 \bullet K^4)}\right]^{1/4} = 285.5\, K$$

Atmosphere temperature:

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

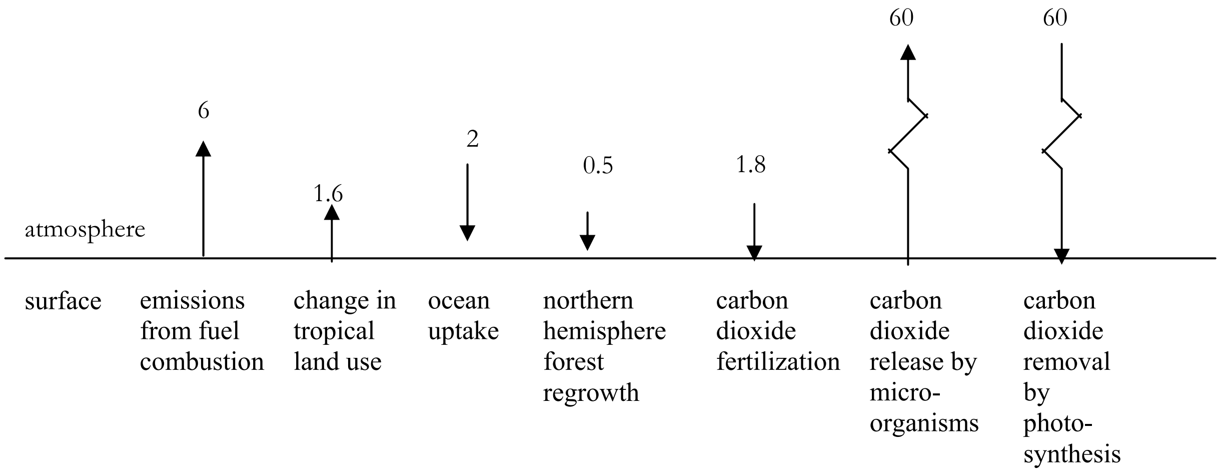
$$T = \left[\frac{y}{.8\sigma}\right]^{1/4} = \left[\frac{162.6\, W/m^2}{(.8)(5.67 \times 10^{-8}\, W/(m^2 \bullet K^4))}\right]^{1/4} = 244.7\, K$$

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.

Solution:
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 <u>carbon</u> per year, where a metric ton is equal to 1000 kg. To calculate the emission and removal rates for <u>carbon dioxide</u>, 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?

<u>Solution:</u>
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

$$= \boxed{(3.3\times10^9 \text{ metric tons / yr})\left(\frac{44 \text{ g}CO_2}{12 \text{ gC}}\right)\left(\frac{10^3 \text{ kg}}{\text{metric ton}}\right) = +1.21\times10^{13} \text{ kg}CO_2 \text{ / yr}}$$

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.

<u>Solution:</u>
+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

$$= \boxed{(3.9\times10^{9}\text{ metric tons / yr})\left(\frac{44\,\text{g}CO_2}{12\,\text{gC}}\right)\left(\frac{10^3\text{ kg}}{\text{metric ton}}\right) = +\,1.43\times10^{13}\text{ kg}CO_2\text{ / yr}}$$

+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

$$= \boxed{(3.9\times10^{9}\text{ metric tons / yr})\left(\frac{44\,\text{g}CO_2}{12\,\text{gC}}\right)\left(\frac{10^3\text{ kg}}{\text{metric ton}}\right) = +\,1.43\times10^{13}\text{ kg}CO_2\text{ / yr}}$$

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 $1.5\text{x}10^{20}$ moles.

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

$$(1.21\times10^{13}\text{ kg}CO_2\text{ / yr})\left(\frac{10^3\text{ g}}{\text{kg}}\right)\left(\frac{1\text{mole}CO_2}{44\,\text{g}CO_2}\right) = 2.75\times10^{14}\text{ moles}CO_2\text{ / yr}$$

Change in mole fraction (ppm) of $CO_2$ =

$$\boxed{\left(\frac{2.75\times10^{14}\text{ moles}CO_2\text{ / yr}}{1.5\times10^{20}\text{ moles air}}\right)\left(\frac{1\text{ppm}}{10^{-6}\frac{\text{moles}CO_2}{\text{moles air}}}\right) = 1.83\text{ppm / yr}}$$

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.

<u>Solution:</u>

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?

<u>Potential Sources of Information</u>
*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

<u>Solution</u>:
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.

<u>Solution</u>:
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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