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:

I2006 = P2006 A2006 T2006

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

I2006/I2006 = (P2006/P2006) (A2006/A2006) (T2006/T2006) = (1.01)44(1.02)44(1) = 3.7

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

I2006/I2006 = (P2006/P2006) (A2006/A2006) (T2006/T2006) = (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

3

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.

Solution:

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.

Solution:

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 \* 106 BTU. To generate this much electricity we need:

BTU primary fuel = 2.05 \* 106 BTU/((1-.1)(.4)) = 5.7 \* 106 BTU

5.7 \* 106 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 (1015)   
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?

Solution:

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

4

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/meter2), *E* the infrared planetary irradiance   
(Watts/meter2), *RE* 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.

*S RE E*

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/m2.

Solution:

Energy Balance:

“Rate of Solar Energy Absorbed” = “Rate of Infrared Energy Emitted”   
 (1-*A*) *S*  *RE*2 = *E* 4  *RE*2

*E*

(1  *A*)*S*

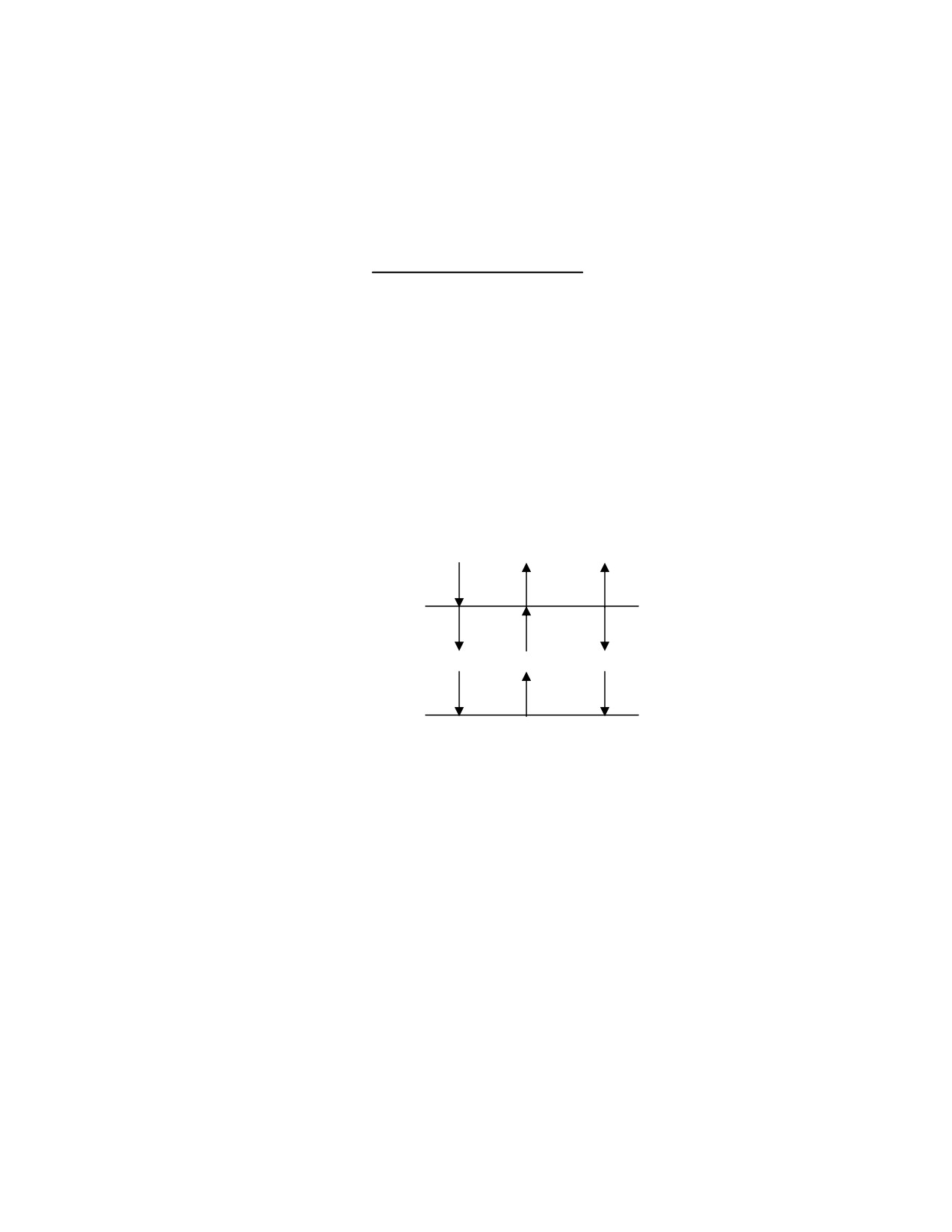
4

 ~~(~~~~1.3)(1,360Watts~~ ~~/~~ *~~m~~*~~2~~~~)~~  238 Watts/ *m*2 4

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* = *σ T4*, *σ* is   
the Stefan-Boltzman Constant (5.67x10-8 Watts/( m2•˚K4)), and *T* is absolute temperature (˚K).

5

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**T*4

*T* 

 1/4 

 238Watts / m2 1/4

    254.5K

5.67  108 Watts / (m2 K4 )

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).

*E*

*.9 E*

*.9 E*

*.2 x*

*x*

*x*

*y*

Atmosphere

*y*

*y*

Surface

Let *x* equal the irradiance (W/m2) 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/m2 from problem 2). At the earth’s surface, a radiation balance requires that

0.9*E* + *y* = *x*

(irradiance in = irradiance out)

while for the atmosphere layer, the radiation balance is *E* + *x* = 0.9*E* + 2*y* + .2*x*

a) Solve these equations simultaneously for *y* and *x*.   
 Solution:

At the earth’s surface, a radiation balance requires that (irradiance in = irradiance out)

6

*E*

0.9*E* + *y* = *x*

while for the atmosphere layer, the radiation balance is

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

Solving these equations simultaneously for *y* and *x* results in

*y*

.82 82

1.2*E*.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   *T*4

*T* 

*x*



1/4

  376.8*W* / *m*2 1/4

    285.5 *K*

 5.67  108 *W* / (*m*2 *K*4 )

Atmosphere temperature:

*y* .8 *T*4

*T* 

 *y*

8

1/4

  162.6*W* / *m*2 1/4

     244.7 *K*

 (.8)(5.67  108 *W* / (*m*2  *K*4 ))

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.

7

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)

60 60

6

2

0.5 1.8

1.6

atmosphere

surface emissions change in ocean northern carbon carbon carbon

from fuel tropical uptake hemisphere dioxide dioxide dioxide

combustion land use forest fertilization release by removal

regrowth micro- by

organisms photo-

synthesis

The numbers in the diagram have units of 109 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 CO2/12 g C).

a) Write a steady state mass balance for carbon dioxide in the atmosphere and calculate the rate   
of accumulation of CO2 in the atmosphere in units of kg/yr. Is the accumulation rate positive or   
negative?

Solution:

A mass balance for CO2 at the earth's surface is

Accumulation of CO2 in atmosphere = rate of CO2 release from surface -

rate of CO2 removal by surface

Accumulation of CO2 in atmosphere (metric tons C/yr) = (60+6+1.6) - (60+2+.5+1.8)   
 = 3.3 metric tons C/yr

=

44 gCO2 (3.3  109 metric tons / yr)

 103 kg    
  1.211013kgCO2 / yr

 12 gC metric ton

b) Change the emission rate due to fossil fuel combustion by +10% and recalculate the rate of   
accumulation of CO2 in the atmosphere in units of kg/yr. Compare this to the change in the rate   
of accumulation of CO2 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%

8

Accumulation of CO2 in atmosphere (metric tons C/yr) = (60+6.6+1.6) - (60+2+.5+1.8)   
 = 3.9 metric tons C/yr

=

44gCO2 (3.9  109 metric tons / yr)

 103 kg    
   1.431013 kgCO2 / yr

 12 gC metric ton

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

Accumulation of CO2 in atmosphere (metric tons C/yr) = (60.6+6+1.6) - (60+2+.5+1.8)

= 3.9 metric tons C/yr

=

44gCO2 (3.9  109 metric tons / yr)

 103 kg    
   1.431013 kgCO2 / yr

 12 gC metric ton

c) Calculate the rate of change in CO2 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 CO2, is the mole fraction of CO2 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 1.5x1020 moles.

Solution:

Change in number of moles CO2 from part a =

103 g1moleCO2

(1.21  1013 kgCO2 / yr)    2.75  1014 moles CO2 / yr

 kg  44 gCO2 

Change in mole fraction (ppm) of CO2 =



2.75  1014 molesCO2 / yr   
 



1ppm

  1.83ppm / yr

 1.5  1020 moles air

   
 10-6 ~~molesCO2~~ 

 moles air 

This rate of change compares well with the observed rate of change of 0.5%/yr, which at the current concentration of CO2 is (.005)(360 ppm) = 1.80 ppm/yr.

d) Describe how the rate of accumulation of CO2 in the atmosphere, calculated in parts b and c,   
would change if processes such as carbon dioxide fertilization and forest growth increase as CO2concentrations increase. What processes releasing CO2 might increase as atmospheric   
concentrations increase? (Hint: assume that temperature will rise as CO2 concentrations rise).

Solution:

The rate of CO2 accumulation would decrease if the processes of CO2 fertilization and forest growth were enhanced by a future global temperature rise. On the other hand, the rate of CO2 accumulation would increase if the processes of CO2 release were accelerated, for example, by microbial metabolism in soil.

9

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, CO2 emissions would decrease by about   
25%, volatile organic compounds (VOCs) and CO decrease by about 80%, NOx would increase   
by about 60%, and SO2 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

10

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](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.](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

11

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](http://www.inece.org/seaport/seaportworkingpaper_24november.pdf/)).

Solution:

Instructor should read the student’s written work and grade according to a chosen rubric