EDUCATION MODULES FOR TEACHING SUSTAINABILITY

in a Mass and Energy Balance Course

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Sustainability is a vital issue for the long-term, healthy development of human society. As the United Nations pointed out, "We cannot carry on depleting natural resources and polluting the earth. The principal aim of sustainable development is to achieve progress on all fronts—economy, environment, and society."[1] The chemical industry, like other manufacturing industries, has been facing tremendous challenges due to economic globalization, environmental pressure, natural resource depletion, etc. The industry fully recognizes its commitment to product stewardship and sustainable development.[2]

Echoing the industrial need and society's expectation, the Accreditation Board for Engineering and Technology (ABET) has specified that sustainability is a key element to be integrated into engineering curricula. Its 2005-06 criteria for program accreditation states: "Engineering programs must demonstrate that their students attain an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability."[3] The quest for sustainability reflects a crucial paradigm shift for the 21st century: the transition from environmental management to systems design—coming up with solutions that integrate environmental, social, and economic factors to radically reduce the use of resources while increasing health, equity, and quality of life for all stakeholders.[4]

SUSTAINABILITY EDUCATION CHALLENGES

A main task in sustainability is to improve the efficiency in material and energy processes in various systems of interest to minimize the need to extract materials and energy from the earth and to reduce any impact to the environment and society. Sustainability is a concept, a process, and a practice very different from traditional chemical process engineering in terms of scope, content, and spatial/temporal aspects. Four types of sustainability systems have been recognized, which range from a global scope to a specific technology[1]: Type I systems address global concerns or problems, such as global warming due to greenhouse gas emissions and ozone depletion; Type II systems are characterized by geographical boundaries, such as cities, villages, or defined ecosystems; Type III systems are

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businesses that strive to be sustainable; and Type IV systems, the smallest in the hierarchy, refer to sustainable technologies that are designed to provide economic value through clean and resource-efficient manufacturing.

It is worth pointing out that the course of material and energy balances in most chemical engineering programs today focuses on balance calculations associated with a process of single- or multiple-process units, such as distillation columns and heat transfer units,[5] which are at the level of Type IV systems in the sustainability hierarchy. Clearly, more complete education addressing sustainability should be incorporated into mass and energy balance coursework. It is thus essential to develop the corresponding educational materials and pedagogical methods for this purpose. In this paper, we introduce several educational modules for addressing the sustainability issues, focusing on mass and energy balance calculations in systems ranging from global to geographical scales. As part of this effort, life cycle aspects of products and renewable energy topics are addressed. Specific examples of problems are provided as follows. This work can be incorporated in a mass and energy balance course, which is usually taken by sophomore students. The modules consist of a set of lecture notes in PowerPoint format and a number of specific problems. The instructor can either assign the problems as homework to the students, or use them as illustrative examples during the lecture. Depending on the length of the lecture, the instructors can choose which module to use and the difficulty level of the problems. The problems in each module are presented in the following sections.

Module 1: Global Carbon and Sulfur Cycles (Type I System - Earth)

Natural cycles of important elements,[6] including the cycles of carbon, nitrogen, oxygen, and sulfur, are critical to environmental sustainability. In this module, students learn how to perform material balance calculations to realize the global impacts of human activities on nature.

A. Carbon cycle

The U.S. Climate Change Science Program[7] reports that the increase in atmospheric CO_2 emissions from human activities is the largest factor contributing to climate change. Globally, about 20.2 gigatons of carbon dioxide per year are emitted to the atmosphere by fossil fuel combustion, and 1.6 gigatons of carbon per year are emitted due to misuse of lands through activities such as deforestation. According to the National Center for Atmospheric Research,[8] the mass of the atmosphere is 5.148×10^{18} kg (or 5.148×10^{6} gigatons) air. Assume that an average global increase in atmospheric carbon dioxide concentration is 2.1 ppm per year, and that all carbon in the atmosphere is contained in carbon dioxide. Much of the carbon that flows through the atmosphere is deposited into various "sinks" on the earth, *i.e.*, on the land and in the water. Of the carbon not accumulated in the atmosphere, 0.5 gigatons is absorbed by trees for photosynthesis, 34 wt% of this carbon is either consumed by non-tree vegetation or accumulated in the soil, and the rest of the carbon is deposited into oceans, lakes, and rivers. With this information, we are able to develop the following challenging problems for students.

Questions:

(a) What is the global flow rate of carbon from the atmosphere into oceans, lakes, and rivers?

(b) If human society could reduce the amount of carbon emitted annually by fossil fuel combustion by 30%, and all other carbon flows remain the same, what would be the global change in atmospheric carbon dioxide concentration annually?

Solution:

(a) To have a better understanding of the problem, develop a flowchart such as that in Figure 1, where the variables of the streams of carbon flows are named. Question (a) asks for calculation of m_7 (gigatons of carbon per year, or Gt C/yr). Problem solving involves two steps: 1) to identify the annual carbon flow from the atmosphere to the earth, *i.e.*, to derive the value of m_4 through a mass balance calculation, and 2) to derive the value of m_7 (the carbon flow to the water—oceans, lakes, and rivers). More detailed calculations are as follows.

Step 1: A basic carbon mass balance in the atmosphere is

$$C_{acc} = C_{in} - C_{out} \tag{1}$$

The carbon generation and consumption terms are omitted in Eq. (1) because atoms cannot be created or destroyed. The carbon accumulation (C_{acc}), input (C_{in}), and output (C_{out}) terms are to be determined using the information given in the problem statement.

$$C_{in} = m_1 \times [MwC] / [MwCO_2] + m_3 \tag{2}$$

$$= 20.2\ [\text{Gt } CO_2] \times 12\ [\text{g C/mol}] / 44\ [\text{g } CO_2\text{/mol}] + 1.6\ [\text{Gt C/yr}]$$

$$= 7.1\ [\text{Gt C/yr}]$$

$$C_{acc} = m_{air} \times x_2\ [MwC] / [MwCO_2] \tag{3}$$

$$= 5.148 \times 10^{18}\ [\text{kg air}] \times 2.1 \times 10^{-6}\ [\text{kg } CO_2 / \text{kg air}] \times 12/44$$

$$= 2.95 \times 10^{12}\ [\text{kg C}]$$

$$= 2.95\ [\text{Gt C/yr}]$$

Thus, the net flow of carbon out of the atmosphere, m_4 (*i.e.*, C_{out}) can be evaluated as:

$$m_4 = C_{out} = C_{in} - C_{acc} \tag{4}$$

$$= 7.1\ [\text{Gt C/yr}] - 2.95\ [\text{Gt C/yr}]$$

$$= 4.15\ [\text{Gt C/yr}]$$

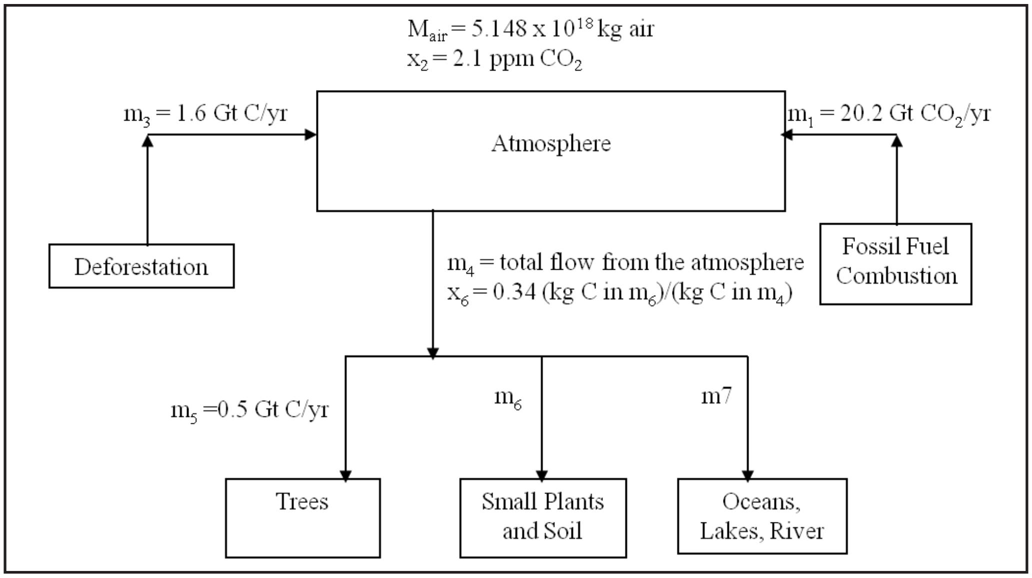


***Figure 1.** Mass balance flowchart derived from the Carbon Cycle.*

Step 2: According to Figure 1, the carbon out of the atmosphere to the earth has the following basic mass balance:

$$C_{in} = C_{out} \tag{5}$$

i.e.,

$$m_4 = m_5 + m_6 + m_7 \tag{6}$$

By using the given information, the amount of carbon flow to the water—oceans, lakes, and rivers—can be readily obtained as follows.

$$m_7 = m_4 - m_5 - m_6 \tag{7}$$

$$= 4.15\ [\text{Gt C/yr}] - 0.5\ [\text{Gt C/yr}] - 4.15\ [\text{Gt C/yr}] \times 0.34$$

$$\boxed{= 2.24\ [\text{Gt C/yr}]}$$

(b) The annual global change in atmospheric carbon dioxide concentration can be evaluated through another atmospheric carbon mass balance calculation. Note that the amount of carbon emitted due to misuse of lands (*e.g.*, deforestation) (*i.e.*, variable m_3 in Figure 1) is known, and the net flow of carbon out of the atmosphere (*i.e.*, m_4) has been derived in part (a). It is assumed that the amount of carbon emitted annually by fossil fuel combustion (*i.e.*, m_1) is reduced by 30%. With this information, the atmospheric accumulation of carbon can be re-calculated, with the stated assumption that all atmospheric carbon is in carbon dioxide. Thus, we can convert the carbon accumulation directly to carbon dioxide accumulation and find the increased annual carbon dioxide concentration. According to the mass balance in Eq. (1),

$$C_{acc} = (m_3 + m_1) - m_4 \tag{8}$$

$$= 1.6\ [\text{Gt C/yr}] + 20.2\ [\text{Gt CO}_2] \times 12\ [\text{g C/mol}] / 44\ [\text{g CO}_2\text{/mol}] \times (1 - 0.3) - 4.15\ [\text{Gt C/yr}]$$

$$= 1.31\ [\text{Gt C/yr}]$$

Equivalently, the accumulated carbon dioxide flow is,

$$CO_{2acc} = 1.31\ [\text{Gt C/yr}] \times 44\ [\text{g CO}_2\text{/mol}] / 12\ [\text{g C/mol}] \tag{9}$$

$$= 4.80\ [\text{Gt CO}_2\text{/yr}]$$

Since the mass of the atmosphere is given, *i.e.*,

$$M_{air} = 5.148 \times 10^{18}\ [\text{kg air}]$$

$$= 5.148 \times 10^{6}\ [\text{Gt air}]$$

if the emissions by human activities are reduced by 30%, the global change in atmospheric CO_2 concentration is reduced from 2.1 ppm to,

$$CO_{2air} = 4.80\ [\text{Gt CO}_2\text{/yr}]) / (5.148 \times 10^{6})\ [\text{Gt air}] \tag{10}$$

$$\boxed{= 0.93\ \text{ppm}}$$

Note that a similar problem was developed by Allen and Shonnard in the textbook *Green Engineering*,[9] Chapter 1, homework problem No. 4.

B. Sulfur Cycle

The modern global sulfur cycle differs quite dramatically from the "pre-industrial" sulfur cycle due to the large portion of anthropogenic sulfur added to the atmosphere each year. Figure 2[10] (next page) illustrates global sulfur fluxes in teragrams per year (Tg S / yr). The illustration shows three distinct control volumes: atmosphere, land, and water. Human mining and extraction, as well as industrial emissions, are the main sources of man-made sulfur emissions to the atmosphere. Sulfur gas emissions from plants, volcanic emissions of sulfur dioxide, biogenic sulfur gas emissions, and sea salt from wind and wave action contribute as the main sources of natural atmospheric sulfur compounds. The atmospheric sulfur compounds can deposit over land and water, and those sulfur compounds in the ocean can form solid sulfur compounds, like pyrite and hydrothermal sulfides. Use the information in Figure 2 to answer the questions that follow.

Questions:

(a) *Draw a flowchart of the entire process using blocks and arrows. Use three blocks to represent the control volumes: one for atmosphere, one for land, and one for bodies of water. Use arrows to represent all flows between control volumes, labeling each stream with its stream name and the quantity of the sulfur flux. Use variables for streams with unknown flows.*

(b) *Calculate the annual accumulation of sulfur (Tg S/yr) in the atmosphere.*

(c) *Calculate the annual accumulation of sulfur (Tg S/yr) in bodies of water.*

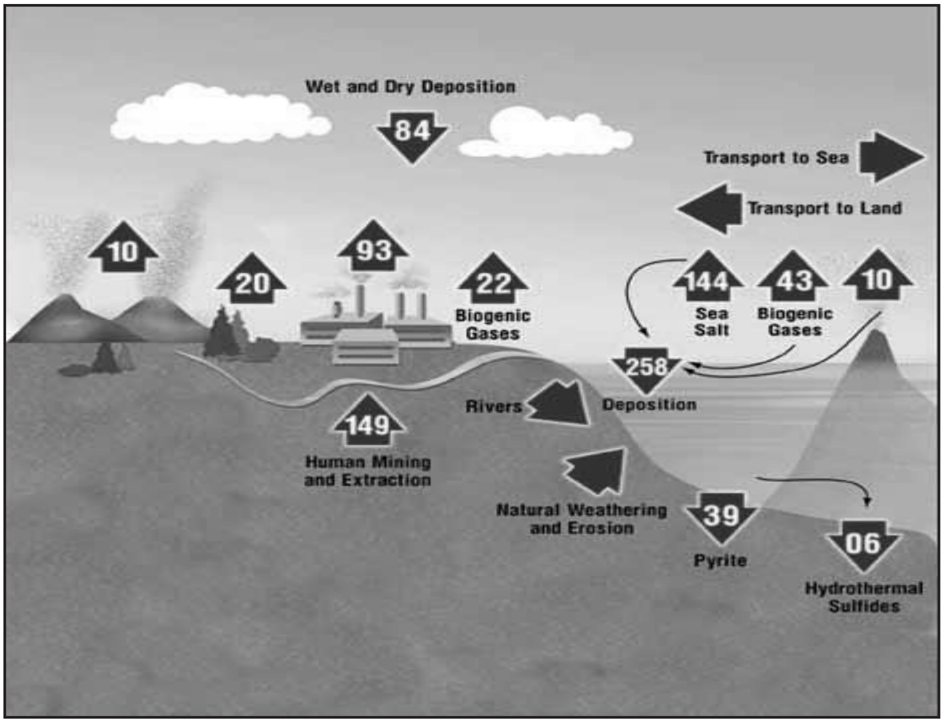


Figure 2. *Illustration of the Sulfur Cycle.*[10]

Solution:

(a) The flowchart is derived by the authors and shown in Figure 3.

(b) Acc = In – Out

$$Acc = (10+20+93+22+149+144+43+10-84-258)\ Tg\ S/yr \tag{11}$$

$$\boxed{Acc = 149 Tg\ S/yr}$$

c) Sulfur balance on water

$$Acc = (258 - 144 - 43 - 10 - 39 - 6)\ Tg\ S/yr \tag{12}$$

$$\boxed{Acc = 16\ Tg\ S/yr}$$

Module 2: Quantification of Material Intensity of an Industrial Ecological System (Type II System) Using AIChE Sustainability Metrics

The second module is the mass and energy flows among various industrial entities in an industrial ecosystem. Figure 4 (page 270) shows the concept of material and energy flow analysis in a larger scope (Type II - regional level). AIChE Sustainability Metrics[11] is a method widely adopted in the chemical industries in the United States. It consists of: (i) Mass Intensity Metrics (including Total Mass Used/$ Value Added, Total Mass Used/$ Value of Product Sold, and Total Mass Used/Mass of Product Sold); (ii) Energy Intensity Metrics (including Total BTU's Conversion Energy Consumed/$ Value Added, Total BTU's Conversion Energy Consumed/$ Value of Product Sold, and Total BTU's Conversion Energy Consumed/Mass of Product Sold); (iii) Pollutant Metrics (including Greenhouse Gas Metric, Photochemical Ozone Creation Potential Metric, Acidification Metric, and Eutrophication Metric); (iv) Human Health Metric; and (v) Ecotoxicity Metric.

This problem utilizes the *AIChE mass intensity* metric, which is defined as total mass in / mass of product sold, as a method for environmental sustain-

TABLE 1
Material Flow Information
(*1000 lbs/yr) (Piluso, et al., 2008)

Variable	Base Case	Modification	Variable	Base Case	Modification
Z10	50.000	50.000	f64	15.033	16.253
Z20	70.000	70.000	f46	0.601	0.650
f31	46.500	46.500	yw01	3.5	3.500
f32	27.720	29.295	yw02	8.4	4.900
f42	33.880	35.805	yw03	8.088	5.239
f33	4.044	8.732	yw04	2.817	2.202
f44	4.025	5.726	yw05	4.356	4.661
f53	68.746	73.352	yp05	78.407	83.895
f35	2.614	2.796	yw06	0.601	0.650
f54	18.373	19.864	yp06	13.830	14.953
f45	1.742	1.864	—	—	—

ability quantification. It is important to note that the smaller the material intensity metric the better, since the material intensity metric is the reciprocal of the "material efficiency," where the larger the better.

Figure 4 displays the variables used in the component-based simplified electroplating supply network,[12] whereas the initial flow values for the base case are supplied in Table 1. This electroplating network consists of two chemical suppliers to the electroplating plants (H1 and H2), two electroplating shops (H3 and H4), and two end users (in this case, two original equipment manufacturers (OEM) for the automotive industry (H5 and H6)). Please evaluate the sustainability situation within the given industrial network using the mass intensity metric:

Questions:

(a) *What is the mass intensity for each of the individual entities (H1, H2, H3, H4, H5, and H6)?*

(b) *What is the mass intensity for the overall system as a whole?*

(c) *If chemical supplier 2 (H2) improves process efficiency and thus reduces waste generation and in addition, both plating shops 1 and 2 (H3 and H4) enhance their in-plant zinc recycling technologies, thereby improving their internal recycle capabilities and thus reducing their waste generation, how will the mass intensity for each of the entities and the overall system change? Calculate and compare with the base case. The flow information for this modification is also given in Table 1.*

Solution:

(a) Based on the definition,

Mass intensity = total mass in / mass of product. (13)

For chemical supplier H1,

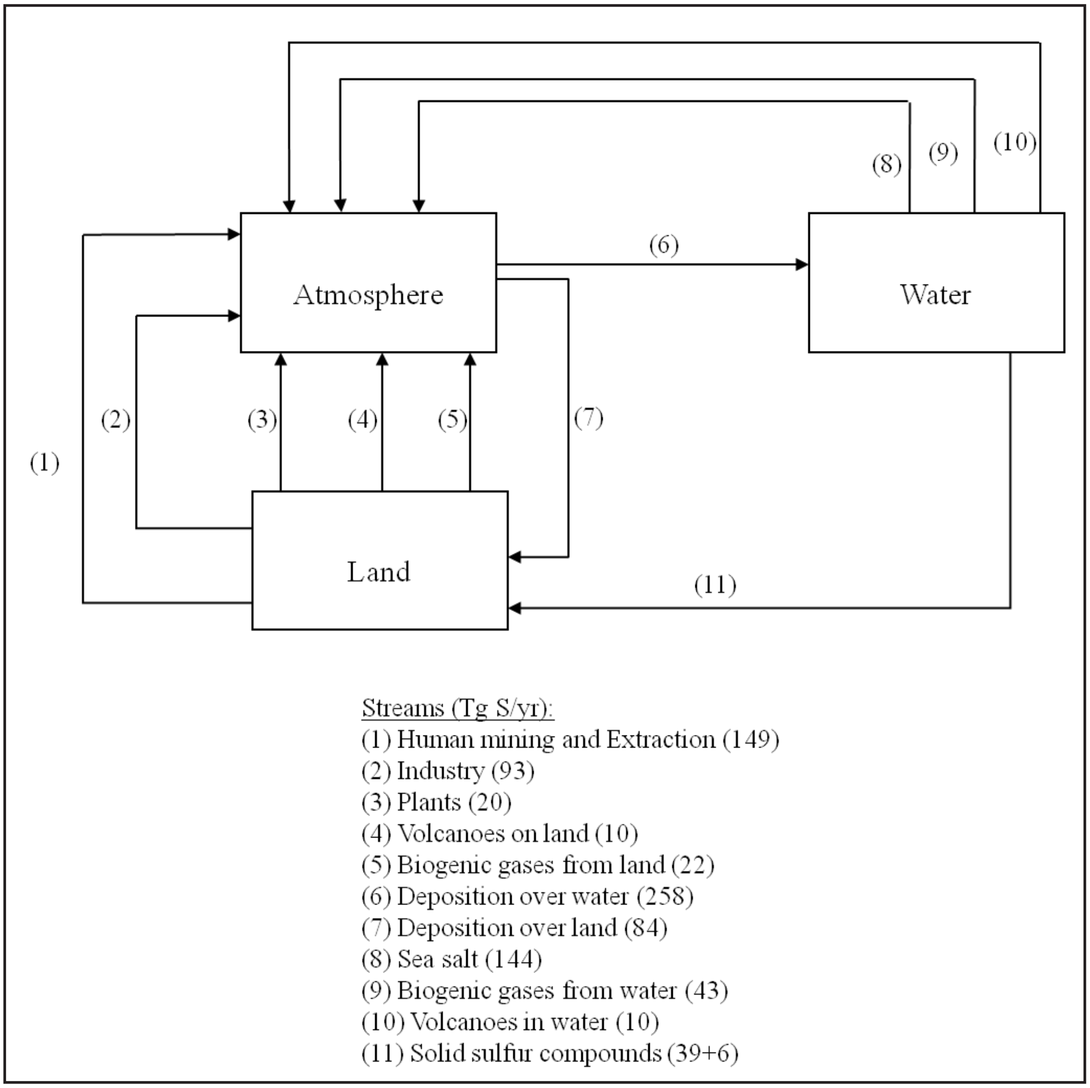


***Figure 3.** Mass balance flowchart derived from the Sulfur Cycle.*

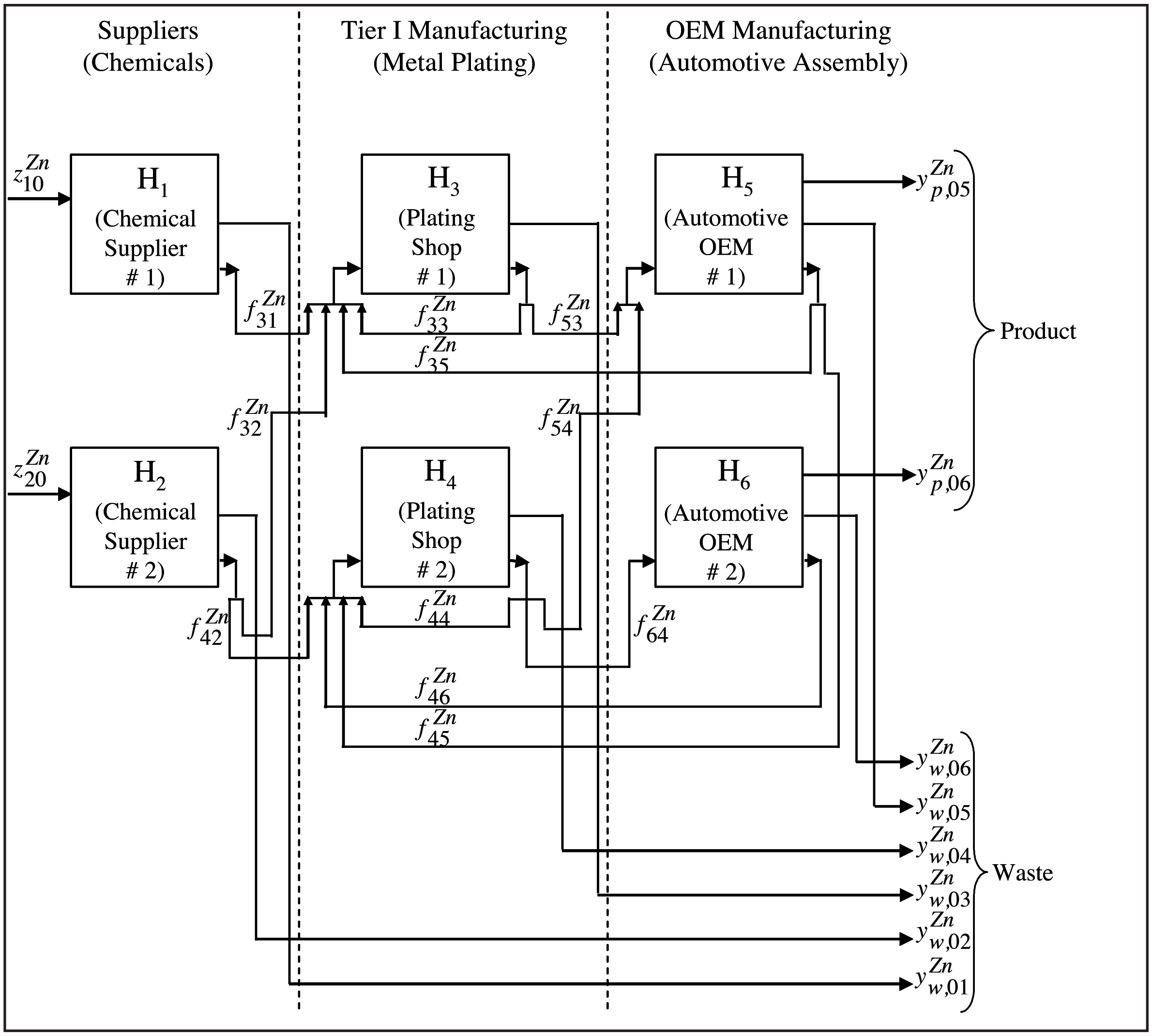


Figure 4. *Schematic diagram of the variables used in the component-based electroplating supply network.*[12]

Total mass in= z10=50.000*1000 lbs/yr

Mass of product=f31=46.500*1000 lbs/yr

So, the mass intensity of H1= z10/ f31 (14)

= (50.000*1000 lbs/yr)/ (46.500*1000 lbs/yr)

=1.075

Similarly, we can calculate the mass intensity for other individual entities.

For H2,

MI (mass intensity) = z20/ (f32+f42) (15)

= (70.000*1000 lbs/yr) / (27.720*1000 lbs/yr +33.880*1000 lbs/yr)

=1.136

For H3,

MI= (f31+f32+f35)/f53 (16)

= (46.500*1000 lbs/yr +27.720*1000 lbs/yr +2.614*1000 lbs/yr)/ (68.746*1000 lbs/yr)

=1.118

For H4,

MI= (f42+f46+f45)/ (f64+f54) (17)

= (33.88*1000 lbs/yr +0.601*1000 lbs/yr +1.742*1000 lbs/yr)/ (15.033*1000 lbs/yr +18.373*1000 lbs/yr)

=1.084

For H5,

MI= (f53+f54)/ (f35+f45+yp05) (18)

= (68.746*1000 lbs/yr +18.373*1000 lbs/yr)/ (2.614*1000 lbs/yr +1.742*1000 lbs/yr +78.407*1000 lbs/yr)

=1.053

For H6,

MI=f64/ (f46+ yp06) (19)

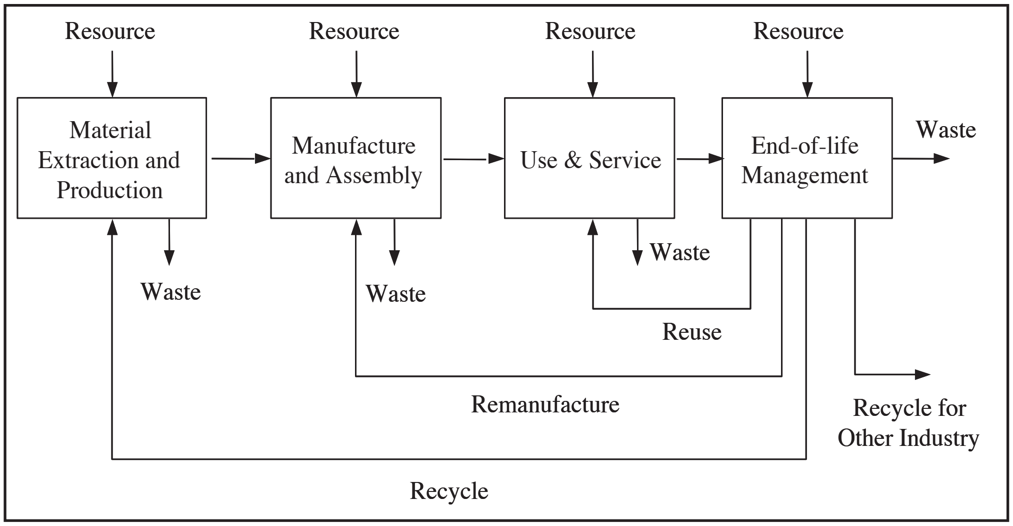


Figure 5. *Schematic of mass and energy flow throughout the life cycle of a product.*[13]

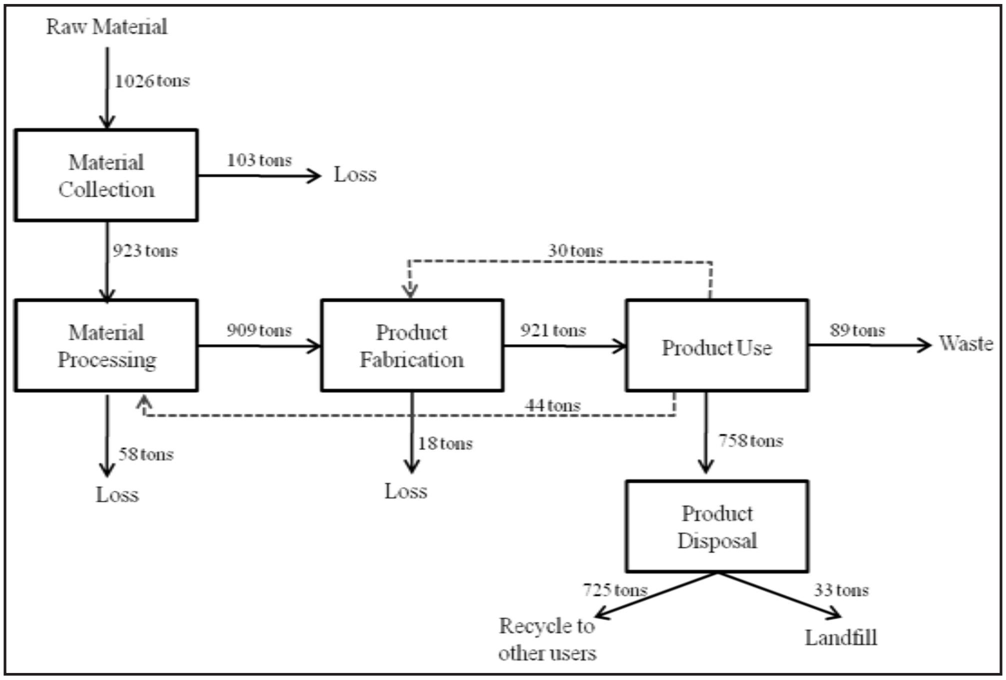


Figure 5(a). *Material flow diagram for Base case.*

= (15.033*1000 lbs/yr)/ (0.601*1000 lbs/yr
+13.83*1000 lbs/yr)
=1.042

(b) For the overall system,
Total mass in=z10+z20
Mass of product=yp05+yp06

So mass intensity for the overall system= (z10+z20)/ (yp05+yp06) (20)
= (50.000*1000 lbs/yr +70.000*1000 lbs/yr)/ (78.407*1000 lbs/yr +13.830*1000 lbs/yr)
=1.301

(c) Similar to the above two questions, substituting the flow rates for the modified case into the equations for mass intensity produces the mass intensity values as shown in Table 2.

Module 3: Mass Balance Throughout a Product's Life Cycle

Sustainability is critical to understanding the mass and energy flows among various industrial entities throughout the life cycle of product(s). A schematic of mass and energy flow throughout the life cycle of a product (adopted from Graedel and Allenby's book in 1998[13]) is presented in Figure 5. In this module, students will use mass efficiency indicator, τ, to quantify the sustainability of each step in the product's life cycle. The formula is this:

τ = Mass of the Product/ Total Mass of the Input Material (21)

Assignment:

(a) *Calculate the mass efficiency of each step in the product's life cycle shown in Figure 5a. Note that this case study and Figure 5a were developed based on Ginley's work*[14] *with modification of the numerical values.*

TABLE 2
Comparison of Two Cases

	Mass intensity	
System type	Base case	Modification
overall system	1.301	1.214
chemical supplier 1 (H1)	1.075	1.075
chemical supplier 2 (H2)	1.136	1.075
plating shop 1 (H3)	1.118	1.071
plating shop 2 (H4)	1.084	1.061
automotive OEM 1 (H5)	1.053	1.053
automotive OEM 2 (H6)	1.042	1.042

TABLE 3
Mass Efficiency of the Steps in a Product's Life Cycle

	Material Collection	Material Processing	Product Fabrication	Product Use	Product Disposal
Symbol	τ_{ME}	τ_{MP}	τ_{PF}	τ_{PU}	τ_{PD}
Value (%)	89.96	94.00	98.08	90.34	95.65

(b) *If there is no recycle from "Product Use" to "Material Processing," to provide 909 unit of feed to "Product Fabrication," how many tons of feed will be needed by "Material Processing" and how many tons of virgin raw materials will be needed by "Material Collection"? Please draw the changed material flow diagram from "Material Collection" to "Material Processing" (assume the mass efficiency of each step remains the same).*

(c) *If there is no recycle from "Product Use" to "Material Processing" and no recycle from "Product Use" to "Product Fabrication," while the customer still needs 921 tons of product, how many tons of feed will be needed by "Material Processing" and "Product Fabrication," and how many tons of virgin raw materials will be needed by "Material Collection"? Is there any change in the amount of landfill generation? Please draw the changed material flow diagram of the entire system (assume the mass efficiency of each step remains the same).*

Solution:

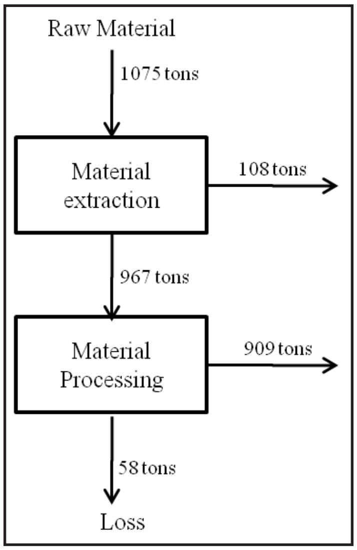
(a) Mass efficiency of the steps in the product's life cycle is provided in Table 3.

(b) By holding all the τ's of each step constant, a reverse calculation provides modified input needed by relevant steps. The changed mass flow from "Material Collection" to "Material Processing" is depicted in Figure 5(b). By comparing Figure 5(a) to Figure 5(b), it is clear that without utilizing the 44 units of recycle stream from "Product Use" to "Material Processing," the demand on the raw material by "Material Collection" is increased from 1026 tons to 1075 tons, while the feed to "Material Processing" is increased from 923 tons to 967 tons. This clearly demonstrates that the 44 tons of recycle stream from "Product Use" to "Material Processing" brings in 1075 – 1026 = 49 units of saving in raw material consumption, and 967 – 923 = 44 tons of saving in virgin material consumption in "Material Processing."

(c) The changed mass flow from "Material Collection" to "Product Use" is depicted in Figure 5(c). By comparing Figure 5(a) to Figure 5(c), it is found that the consumption of raw material by "Material Collection" is increased from 1026 tons to 1110 tons (1110 – 1026= 84 tons), the feed to "Material Processing" is increased from 923 tons to 999 tons, and the feed to "Product Fabrication" is increased from 909 tons to 939 tons, in order to provide 921 tons of product to the consumer. In the meantime, the amount of landfill increases from 33 to 36 tons.

This set of exercises clearly illustrates the following concepts and principles in sustainability:

1. Mass balance not only occurs in production units and in the plant, but also occurs throughout the entire life



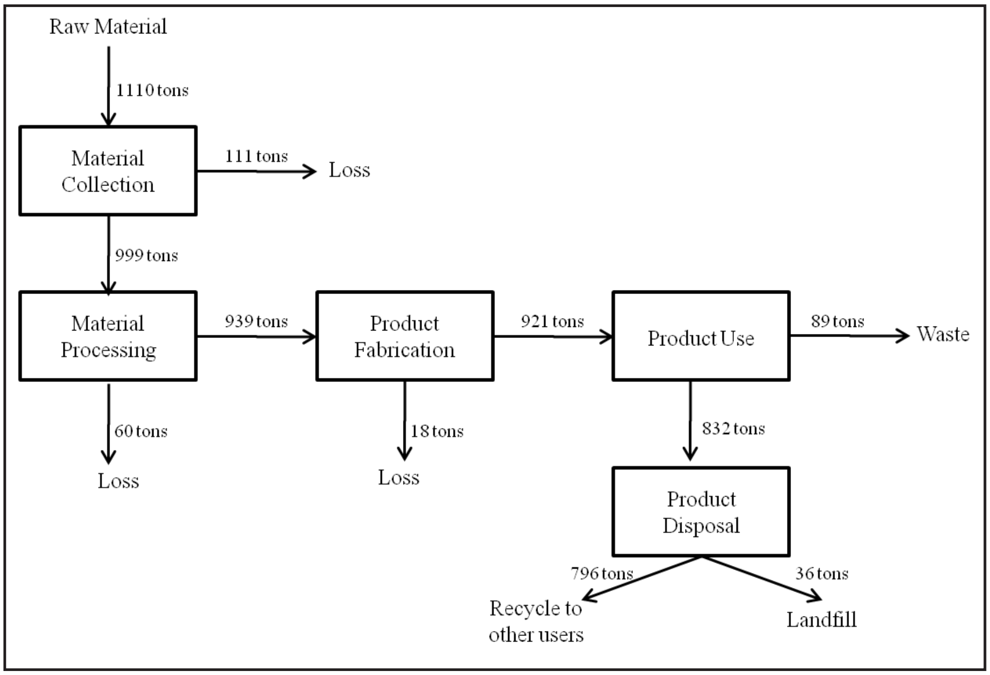


Figure 5(b), above. *Material flow diagram for Case B.*
Figure 5(c), right. *Material flow diagram for Case C.*

cycle of the product from a temporal point of view.

2. If any manufacturing steps (from raw material extraction to product fabrication) or the product use can't utilize 100% of the mass input, some resources will become "waste" or "loss." Waste or loss can be recovered with appropriate technologies, however.
3. To recover the values hidden in the waste, the "waste" can be recycled or reused in various stages through the product's life cycle.

Module 4: Mass and Energy Balance of Biodiesel Production From Soybean (Type IV System)

This module was developed from literature using the first law of thermodynamics to analyze the efficiency of biodiesel production from soybean oil. The paper was contributed by Dr. Tad W. Patzek at the University of California Berkeley.[15] Soybean biodiesel is formed from the transesterification reaction of methanol with the triglycerides that comprise soybean oil. As shown in Figure 6(a), in this biorefinery, harvested soybeans are crushed to separate the soybean oils. The separated soybean oil (stream 3) is 92.2 wt% of the oil in the soybean feed. The oil is then reacted with excess methanol. Distillation is used to separate unreacted oils and excess methanol, and the final biodiesel product stream contains 91.7 wt% of the separated soybean oil. Following the first law of thermodynamics, the efficiency of this biorefinery regarding biodiesel production can be calculated by counting the mass and energy flows in Figure 6(a). In light of sustainability, however, the biodiesel production process is only one step in the overall life cycle of the biodiesel. The efficiency of the upstream process, *i.e.*, the soybean farming (Figure 6b) also needs to be considered. The developed education module is presented below:

(a) Calculate the mass of soybeans required to produce 1 kg of biodiesel. What is the mass efficiency, η_m, for the biodiesel production process?

η_m = (kg of Biodiesel Fuel) / (kg of Harvested Soybeans)

(b) The heating value of a substance refers to the amount of energy released upon combustion. The higher heating values (HHV) of the components in soybeans are 16.5 MJ/kg for soybean meal, 39.6 MJ/kg for soybean oil, and 18.2 MJ/kg for soybean hulls (both water and dirt have zero heating value). Using the compositions shown for stream 1 in Figure 6(b), calculate the overall HHV of soybeans in MJ/kg soybean.

(c) Use an energy balance to calculate the energy losses from the system per kilogram of biodiesel produced. The total energy of fossil fuels entering the process (including the fossil fuels needed for methanol feed production) is 30.7 MJ/kg. The HHV of biodiesel is 40 MJ/kg.

(d) Calculate the energy efficiency, η_e, of biodiesel production:

η_e = (Output Biodiesel Energy) / (Refinery Energy Inputs)

(e) Harvesting of the soybean crop has approximately 64% efficiency ($\eta_e = 0.64$). Calculate the overall energy efficiency of the combined farming and biodiesel refining process.

(f) In 2004, the United States consumed 45 billion gallons of petroleum diesel fuel (HHV = 45.9 MJ/kg and density = 840 kg/m_3). In 2005, more than 210 billion kilograms of soybean was produced worldwide. If the entire world crop of soybean were converted to biodiesel, would it be enough to meet U.S. diesel fuel demand?

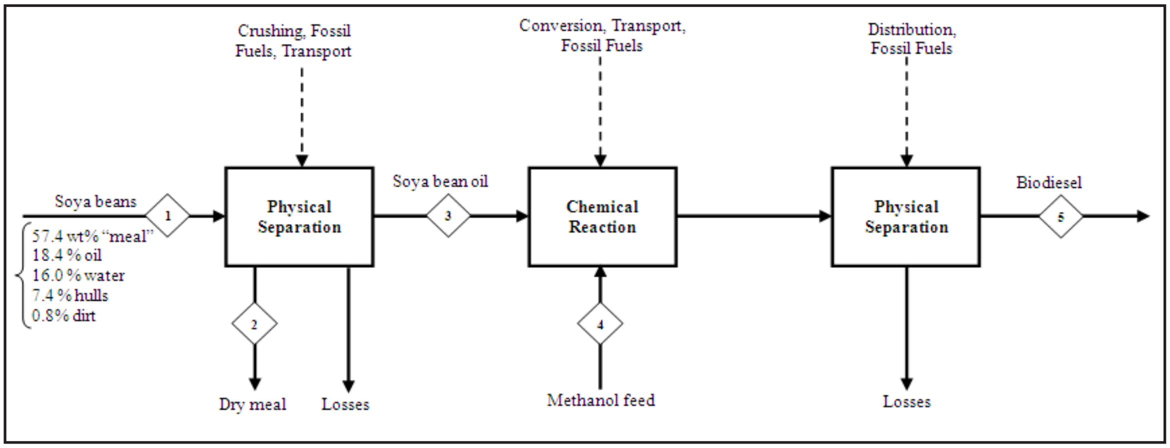


Figure 6(a). *Flowchart of biodiesel production from soybeans.*

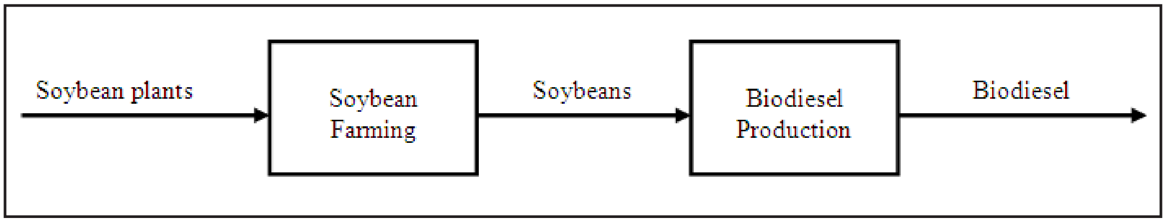


Figure 6(b). *Soybean flow through overall biodiesel production process.*

Solution:

(a) Use a basis of m_5 = 1 kg biodiesel product. Stream 5 contains 91.7 wt% of the material in stream 3. Thus,

$$m_3 = m_5 / 0.917 \quad (22)$$

Stream 3 contains 92.2 wt% of the soybean oil in stream 1. Thus,

$$m_1 \times 0.184 \times 0.922 = m_3 \quad (23)$$

Solving for m_1 gives,

$$m_1 = m_5 / (0.917 \times 0.184 \times 0.922) \quad (24)$$

$$\boxed{m_1 = 6.43 \text{ kg soybeans}}$$

$$\eta = (1 \text{ kg biodiesel product}) / (6.43 \text{ kg soybean feed}) \quad (25)$$

$$\boxed{\eta = 0.156}$$

For every kilogram of soybean fed to the system, 0.156 kilograms of biodiesel are produced.

(b) Overall HHV

=HHV of soybean oil + HHV of soybean hulls+ HHV of soybean meal (26)

$$= (0.184 \times 39.6 \text{ MJ/kg}) + (0.074 \text{ x } 18.2 \text{ MJ/kg}) + (0.574 \times 16.5 \text{ MJ/kg})$$

$$\boxed{\text{Overall HHV} = 18.1 \text{ MJ/kg}}$$

(c) Steady state energy balance (energy flows are per kg biodiesel):

Input = Output

$$\text{Energy of Soybeans} + \Sigma \text{ Fossil Energy} = \text{Energy of Biodiesel} + \text{Energy of Meal} + \text{Losses} \quad (27)$$

$$\text{Energy of Soybeans} = 6.43 \text{ kg of soybeans x } 18.1 \text{ MJ / kg soybeans} \quad (28)$$

$$\Sigma \text{ Fossil Energy} = 30.7 \text{ MJ / kg} \quad (29)$$

$$\text{Energy of Biodiesel} = 40 \text{ MJ / kg} \quad (30)$$

$$\text{Energy of Dry Meal} = 6.43 \text{ kg of soybeans} \times 0.574 \times 16.5 \text{ MJ / kg soybean meals} \quad (31)$$

$$\text{Energy Losses} = (6.43 \times 18.1 \text{ MJ}) + (30.7 \text{ MJ}) - (40 \text{ MJ}) - (6.43 \times 0.574 \times 16.5 \text{ MJ}) \quad (32)$$

$$\boxed{\text{Energy Losses} = 46.18 \text{ MJ / kg biodiesel}}$$

(d) Energy efficiency

$$\eta_e = (\text{Output Biodiesel Energy})/(\text{Energy of Soybeans Inputs+ Energy of Total Fossil Fuels inputs})$$

$$=(40 \text{ MJ}) / (116.38 \text{ MJ} + 30.7 \text{ MJ}) \quad (33)$$

$$\boxed{\eta_e = 0.27}$$

(e) $\eta_e = \eta_{farming} \times \eta_{biodiesel}$ (34)

$$\eta_e = 0.64 \times 0.27$$

$$\boxed{\eta_e = 0.17}$$

(f) The key here is to understand that the demand for diesel is actually an energy demand. The energy of petroleum diesel consumed each year would need to be replaced by an equivalent supply of biodiesel energy. If enough farmland exists to produce the soybeans necessary to meet the energy demand, then soybeans could replace petroleum as a diesel feedstock.

First, determine the current energy demand. This is done by the following unit conversion:

$$\text{Energy demand} = (45.9 \text{ MJ / kg}) \times (840 \text{ kg / m}^3) \times (\text{m}^3 / 264.17 \text{ gal}) \times (45 \times 10^9 \text{ gal fuel})$$

$$\text{Energy demand} = 6.568 \times 10^{12} \text{ MJ} \quad (35)$$

Second, use the heating value and density of biodiesel to determine the mass of biodiesel needed to meet this energy demand:

$$\text{Biodiesel mass} = (6.568 \times 10^{12} \text{ MJ}) \times (\text{kg / 40 MJ}) \quad (36)$$

$$= 1.642 \times 10^{11} \text{ kg biodiesel}$$

Finally, determine the amount of soybean needed to produce this quantity of biodiesel:

$$\text{Soybean mass} = (1.642 \times 10^{11} \text{ kg biodiesel}) / (0.156 \text{ kg biodiesel / kg soybean})$$

$$= 1.05 \times 10^{12} \text{ kg soybean} \quad (37)$$

This quantity of soybeans required to meeting U.S. energy requirements is five times greater than the amount produced worldwide (210 × 10^9 kg soybean). Therefore, soybean biodiesel alone cannot replace petroleum diesel in the United States.

CONCLUSION

This paper reports several educational modules for teaching sustainability in a mass and energy balance course. The systems in these modules range from global scale to industrial ecosystems. The life cycle of product and renewable energy are addressed. These modules will help awaken students' eco-consciousness and establish the students' conceptual understanding of the systems concept in sustainability.

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