

Life Cycle Assessment of Biofuels 101



Overview: When selecting alternative fuels, it is important to consider the relative advantages and disadvantages of each. This activity asks students to begin to consider the life cycle energy and carbon dioxide emission costs of gasoline, corn ethanol and cellulosic ethanol. The various pieces help students trace energy and matter through a complex system and begin to critically analyze graphical comparisons of different fuels.

Levels

6 through Undergraduate

Subjects

Science, Environmental Studies

Objectives

Students will:

- Trace energy and carbon through a transportation fuel production system.
- Identify ways to process transportation fuels without the use of fossil fuels.
- Describe steps in fuel processing where carbon dioxide is sequestered and released.
- Evaluate the sustainability of gasoline, corn ethanol and cellulosic ethanol.

Materials

- Biofuels 101 Package
- Supplementary Videos - Available Online.

Activity Time

Two or three 50-minute class periods

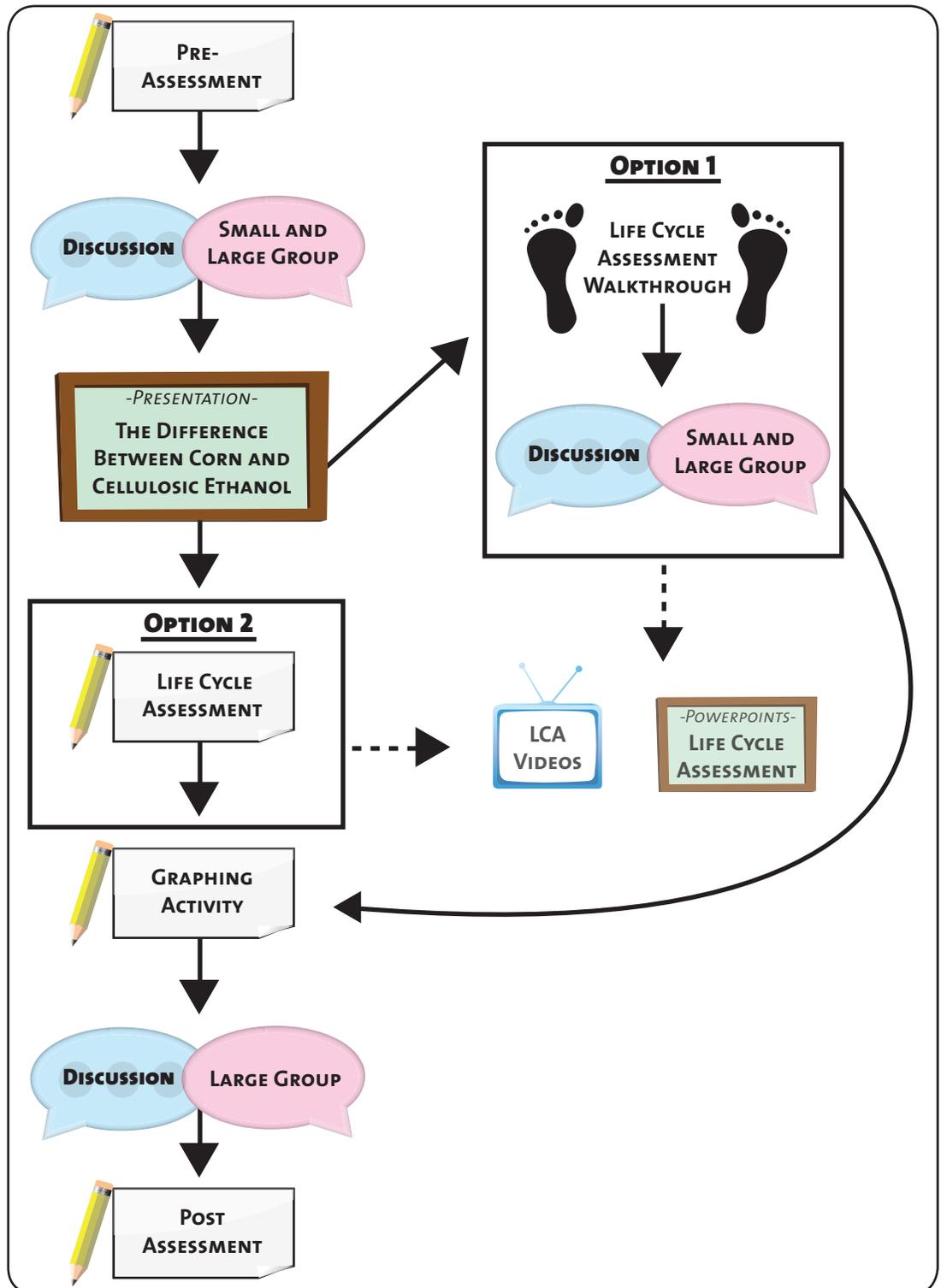
Standards

Next Generation Science

Standards (2013)

- Scientific and Engineering Practices: developing and using models; engaging in argument from evidence; obtaining, evaluating, and communicating information
- Disciplinary Core Ideas: matter and its interactions; ecosystems; earth and human activity; engineering design
- Crosscutting Concepts: energy and matter
- Performance Expectations: See page 3 for details

NGSS Lead States. 2013. *Next Generation Science Standards: For States by States*. Washington DC: The National Academies Press



For Teachers - Life Cycle Assessment of Biofuels 101

Overview:

When selecting alternative fuels, it is important to consider the relative advantages and disadvantages of each. This activity asks students to begin to consider the life cycle energy and carbon dioxide emission costs of gasoline, corn ethanol and cellulosic ethanol.

This lesson is designed to run over the course of two or three 50 minute class periods. Given the complexity of the material, allow plenty of time for discussion and questions.

Learning Outcomes: Students will...

- Trace energy and carbon through a transportation fuel production system.
- Describe steps in fuel processing where carbon dioxide is sequestered and released.
- Identify ways to process transportation fuels with fewer inputs of fossil fuels.
- Evaluate the sustainability of gasoline, corn ethanol and cellulosic ethanol production.

This lesson assumes prior knowledge in the carbon cycle, energy transfer, some discussion of global climate change and energy crisis.

Standards

Next Generation Science Standards (2013)

Performance Expectations

Middle School:

- **MS-LS2-3.** Develop a model to describe the cycling of matter and flow of energy among living and nonliving parts of an ecosystem.
- **MS-ESS3-3.** Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment.
- **MS-ESS3-4.** Construct an argument supported by evidence for how increases in human population and per-capita consumption of natural resources impact Earth's systems.
- **MS-ETS1-1.** Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.

High School:

- **HS-ESS3-2.** Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios.
- **HS-ESS3-4.** Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.
- **HS-ETS1-1.** Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

Next Generation Science Standards (continued)

Scientific and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS1: Matter and its interactions LS2: Ecosystems: Interactions, energy, and dynamics ESS3: Earth and human activity ETS1: Engineering design	Energy and matter: Flows, cycles, and conservation

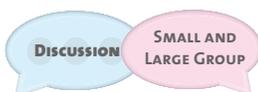
See Appendix for alignment with other standards.

Sequence:



Part 1. Pre-assessment of student knowledge on biofuels and sustainability (pages 1 and 2) (30–40 min)

Ask each student to complete page 1 on his or her own. They may need prompting to make the drawing, depending upon their familiarity with drawing the carbon cycle.



Students should complete page 2 in small groups. All students should write answers, but you may want them to designate one individual as the official recorder and another as the official reporter for class discussion later.

Large group discussion on page 2. Ask each group to report on at least one area of agreement and one area of disagreement or question. This is a chance for the teacher to assess student knowledge, misconceptions and questions about biofuels. There is no need to answer their questions at this point, except perhaps that a gallon of ethanol contains 2/3 the energy of a gallon of gasoline and confirmation of the carbon cycle. Most statements could be answered either way depending on facts used.



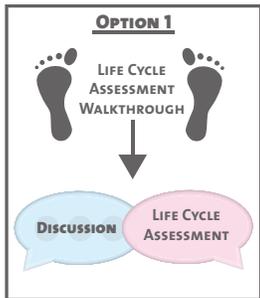
“Cellulosic Ethanol”

Part 2. Provide background information (time varies by teacher choice).

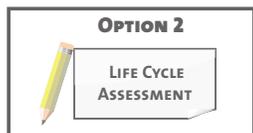
In order to complete the rest of this exercise, students will need a basic understanding of the difference between corn ethanol and cellulosic ethanol. This could be done as a lecture or reading (see included “cellulosic ethanol” reading or other suggested background material in the appendix). The fundamental difference is corn ethanol is created from corn grain, a starchy material, which is fairly easy to ferment. Amylase and heat can break starch into glucose, which is readily fermentable. Corn ethanol feedstock comes from farms. Cellulosic ethanol is created from leaves, stems, woody materials, which are not easy to ferment. Enzymes to digest cellulose are not readily available industrially, and a great deal of energy and chemicals currently go into isolating the cellulose and preparing it for fermentation. Source material for cellulosic ethanol could come from farm residues, yard waste, prairie grasses and a host of other feedstocks.

Part 3. Introduction to Life Cycle Assessment (pages 3-7) (30-40 min)

This is a qualitative overview of the process used by scientists, and required by the National Renewable Fuels Standard program, for determining if these new fuels are sustainable. There are two options for this part of the activity-- the paper version, described below, or the “Walkthrough.” The Walkthrough LCA of Biofuel Production (p. 3-4, instructions on 6T) is a cooperative, active full-class version of the paper activity where teams solve energy and matter transformations at one station and connect what they learned to the other stations. They “walk” energy and carbon forms through the process of making biofuel using manipulatives and a process tool. *The Life Cycle Assessment Process Tool* can be used as homework or as a test after completing the walkthrough to assess whether or not the students understand the flow of energy and matter through the cycle.



“Walkthrough”



The paper activity (p. 5-7) leads the students through each part of the assessment separately (energy first, then CO₂). It may help to talk students through the energy transformations involved--discussing how the sun provides energy to the plants and then that energy is transformed into chemical energy which is burned at various points in the cycle. Students may wish to draw arrows showing energy entering or escaping the system. Allow students to fill in the carbon dioxide chart on their own or with a partner depending on their comfort with the carbon cycle. The follow-up questions may be best discussed in partners before discussion as a class.



“LCA Carbon and Energy animated presentations and scripts”



“LCA of Carbon and Energy online videos”

Animated PowerPoints and videos of the energy and carbon flows are available in the supplementary materials folder in the activity package and on the GLBRC website respectively. These are useful reviews of the material, and the videos provide supplementary photographs and interviews.

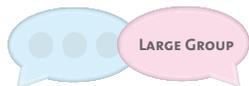
Teaching Tip: Tracing energy and carbon through systems can be difficult for many students. Students will often try to transform matter into energy and vice versa, or allow carbon to turn into oxygen. Work through the inner loop of plant energy or carbon first. Then discuss external inputs and outputs. Distinguish between quick cycling plant energy and materials, and longer cycling fossils fuels. The PowerPoints and scripts can provide a chance to hear, see and read the answer after students attempt to work through it on their own.



Part 4. Graphs. Comparing energy used to create gasoline, corn ethanol and cellulosic ethanol. (pages 8-11) (30-40 min)

Complete pages 8 and 9 individually or in pairs. Students may need prompting to think about why fossil fuels are needed to create fuel.

Discuss answers with students. Please look at teacher answers provided for guidance.



The last question is meant as a self-assessment for you and for the student. What did they learn from the activity and what further questions do they have? This may lead into deeper research into the quantitative studies on biofuel sustainability.

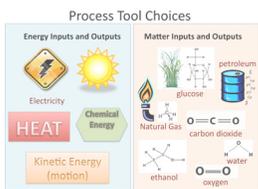
Extension

Follow up references included in the appendix. Also visit the GLBRC education page for additional activities related to this topic.

(Option 1) - Walkthrough Life Cycle Assessment of Biofuel Production Instructions for Educators



1. Print out one full page version of the six LCA stations (slides 1-7) and post around the classroom.
2. Print out seven copies of the Process Tool on slide 8 and hang one under each station. The refinery station should have two copies, one for fermentation and the other for plant operation.
3. Print out copies of process tool cards (slides 10-13). Number of copies of each is indicated at the bottom of the slide. Cut the slides apart so each process is separate.
4. Assign at least two students to stand at each of the six stations. Other students may watch, help, or complete the activity on paper individually.
5. Show slide 9, with all of the process tool options. For students standing at each station, ask them to think about the process that occurs at their location. They should identify the energy input(s) and energy output(s) as well as the matter input(s) and output(s) and write that on the process tool page. For example, students at the Plants station would pick up the sun as their energy input and chemical energy as the energy output. CO₂ and H₂O are matter inputs, glucose and O₂ are matter outputs. They can then pick up cards to represent each item. Note: the Refining station has two substations: plant operation and fermentation. There may be extra cards left over.
6. After students have chosen their cards, they should explain their choices to the class. The class should walk through the cycle in order, following the arrows first from plants (photosynthesis) to the refinery (fermentation) to the car (combustion), then going through farming practices, feedstock transport, refinery (plant operation) and product transport. Correct any mistakes students make along the way. Cards can be passed from one group to another or taped to the process tool.



7. Be sure students have a chance to see the visual of the complete cycle as it appears in the printed activity (slide 14) so they can see the cycle as well as walking and talking about it. Bring the process tools together on the front board at the end of class if it is useful.
8. Followup questions: In order for ethanol production to be carbon neutral, what would need to happen? Where along the way could you modify the system to reduce the total amount of carbon dioxide released into the atmosphere? Are there other choices that could be made that would make the system less damaging to the environment?

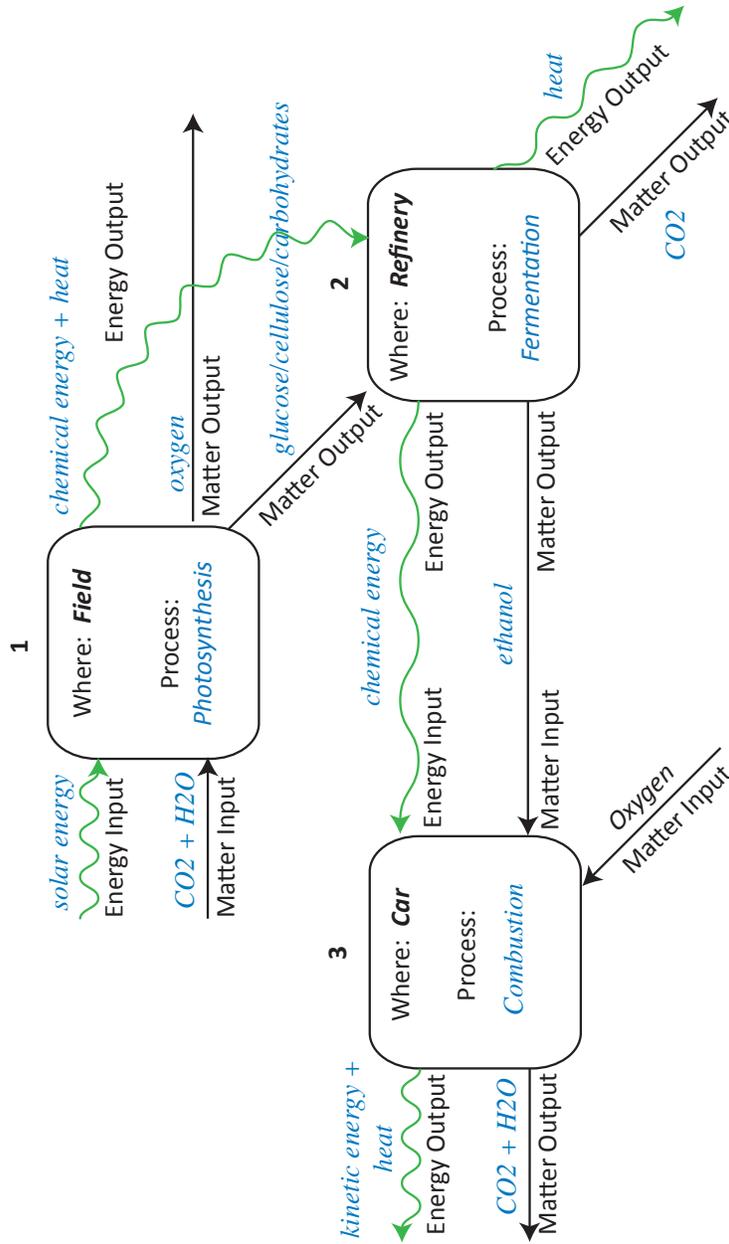


"LCA Carbon and Energy animated presentations and scripts"



"LCA of Carbon and Energy online videos"

(Option 1) - Life Cycle Assessment Process Tool (p. 3-4)



Please note that these answers show the primary energy inputs and outputs associated with fuel production. There are other energy losses in the system not shown here. Teachers could discuss the efficiency of plant growth and photosynthesis, energy content of CO_2 and H_2O as well.

Follow-up questions:

1. What is the relationship between the matter output from #3 to the matter input in #1? They are the same. CO_2 leaving cars returns to the atmosphere where it could enter more plants through photosynthesis. This part of the loop alone is carbon neutral for that reason.
2. Does all energy put into #1 make it to the energy output stage of #3? Why or why not? No, much energy in the diagram is lost as heat or through organismal metabolism, like yeast, during fermentation (not modeled here).
3. If we are conducting a life cycle assessment for energy or greenhouse gases, like carbon dioxide, why can't we stop at stages 1-3? Why do we need to include stages 4-7 as well? Because more energy is needed to farm and move plants around, to actually run the refinery, and in other places. A life cycle assessment looks broadly at energy and matter inputs and outputs necessary to create the fuel.

Additional inputs to create biofuel. (p. 4)

Note that answers for 4-7 will vary considerably. Fuel sources will vary for transportation use; refineries will often use multiple energy sources to power different parts of the refinery. For example, methane (natural gas) may be used to heat materials during pretreatment, but biomass may be burned to generate electricity or heat a fermenter. Some refineries generate enough electricity at this stage to sell excess to the grid.

Follow-up questions:

- Describe how you would determine the net energy gain or loss for ethanol production. Write an equation using only the relevant steps. You can abbreviate EI for Energy Input and EO for Energy Output (eg. EI #1 - EO #7=). *There are many ways to answer this question. Students should be reminded the energy in = energy out for the system. Net energy input is EI 1 - EI 4 - EI 5 - EI 6 - EI 7. (solar energy in minus fossil fuel inputs). Alternatively, engineers calculating a life cycle assessment might use EO 2 - EI 4 - EI 5 - EI 6 - EI 7 (energy in ethanol minus fossil fuel inputs to create it). Balancing renewables and non-renewables is a common way to look at the problem.*
- How do you think you could best improve the energy efficiency of this process? Reduce the carbon footprint? *Energy: reduce losses to heat, shorten transportation distances, lower energy needs for conversion of fuel; Carbon footprint: increase energy efficiency, use of renewable energy for electricity, transportation, etc.*

(Option 2) - Life Cycle Assessment (p. 5-7)



1. Try your own life cycle assessment (variations on the steps are acceptable)

Steps:	Carbon Sequestered or Released?	Form of carbon (from __ to __)	How or why? (Photosynthesis, cellular respiration, combustion)
<i>Planting crop</i>	<i>Released</i>	<i>Gasoline to CO₂</i>	<i>Combustion</i>
<i>Grow crop</i>	<i>Sequestered</i>	<i>CO₂ to glucose, etc.</i>	<i>Photosynthesis</i>
<i>Harvesting crop</i>	<i>Released</i>	<i>Gasoline to CO₂</i>	<i>Combustion</i>
<i>Transporting crop</i>	<i>Released</i>	<i>Gasoline to CO₂</i>	<i>Combustion</i>
<i>Creating Ethanol</i>	<i>Released</i>	<i>Coal, gas, biomass to CO₂</i>	<i>Combustion</i>
<i>Transporting Ethanol</i>	<i>Released</i>	<i>Gasoline to CO₂</i>	<i>Combustion</i>
<i>other...</i>			

2. In order for ethanol production to be carbon neutral, what would need to happen?

Sum of carbon dioxide sequestered in photosynthesis = sum of carbon dioxide released in other processes in cycle

Because all of the C released during ethanol combustion was sequestered during growing, those 2 processes are a net zero. Therefore, there needs to be an additional C sink from plant matter left behind that becomes permanently trapped in soil to offset the additional C from the other industrial processes and the release of other global warming gases that result from growing crops. Perennial crops where roots and base shoots are left intact can help meet those needs. IN REALITY...biofuels are not C-neutral, but with good management practices they can release LESS greenhouse gases when compared with gasoline. See Appendix for further reading.

3. Where along the way could you modify the process to improve it to reduce the total amount of carbon dioxide released into the atmosphere? Are there other choices that could be made that would make the overall process more environmentally friendly?

Use perennial crops and harvest only above ground matter to reduce planting costs, and to maintain carbon in roots. Burn plant material in refining process. Reduce transport distances, use waste from refining process to feed cows and fertilize soils. These practices also benefit water quality through reduced erosion and runoff. Land use changes are also important to consider. Cutting down a forest to grow energy crops, for example, releases more CO₂ that was sequestered over decades or centuries and is damaging to the atmosphere. See Appendix.



**GRAPHING
ACTIVITY**

Collecting evidence to support your opinions... (p. 8-11)

1. Why would you need to use fossil fuels to create gasoline and ethanol? Think of at least 3 examples for each fuel (remember fossil fuels include petroleum, coal and natural gas).

For gasoline, energy is needed to: drill a well, move oil to the refinery either by pumping through a pipeline or to move a tanker ship across the ocean, provide heat for chemical processing at the refinery, ship and truck the refined gasoline from the refinery to blending stations and then to the gas station, make the equipment and machines to do any of the above activities.

For ethanol, energy is needed to: make fertilizer and other farming chemicals, run tractors and machines for planting, spraying, and harvesting crops, bring the harvested crop (corn or cellulosic biomass) to a biorefinery, convert the biomass into ethanol (electricity to run chopper to cut up plants before fermentation, heat to distill ethanol, etc). ship and truck the ethanol from the biorefinery to blending stations and then to the gas station.

2. Students complete graph and compare to figure 4.
3. Which fuel do you think will require the greatest amount of energy to manufacture? Why?

Answers will vary.

4. Why is the output bar for one fuel source always lower than the input?
Inefficiencies of energy conversion. Second law of thermodynamics states that energy systems have a tendency to increase their entropy. Much energy is lost to heat in the conversion processes.

BTU required per BTU of Fuel... (p. 10-11)

1. The dashed line is equivalent to what on figure 3?

Energy Output Bars

2. Do the vertical bars represent energy inputs or outputs?

Inputs

3. Which fuel currently requires the most BTUs to produce?

Cellulosic Ethanol

4. Which fuel requires the least amount of fossil fuels to produce?

Cellulosic Ethanol

5. The efficiency on the graphs refers to the amount of energy needed to produce the transportation fuel.

Which fuel is most efficient? *Gasoline*

What percent? *81%*

6. If gasoline is most efficient, why would we even consider making ethanol from corn or cellulosic biomass?

Because BTUs from combustion of plant material do not contribute to climate change.

Biorefineries often burn plant material to create electricity to run the machinery or generate heat to distill the ethanol instead of using coal or natural gas. The CO₂ released from combustion of plant material, was recently sequestered from photosynthesis and will be returned to plant material in short time (months or years). BTUs from combustion of fossil fuels cycle over hundreds of millions of years and will remain in the atmosphere.

7. Why is the measurement for corn ethanol almost the same as gasoline?

Refer to processes covered in previous section on life cycle assessment. Farming is fossil fuel intensive, as is drilling, refining and transporting petroleum.

8. The bar for corn ethanol includes possible changes in land use to grow additional acres of corn. Is this land use change inevitable? Are there alternatives the United States could consider to prevent land use changes?

Many possible answers. Much corn in the US does not directly feed humans, it feeds animals. Ways might found to grow more corn on existing acreage without increasing emissions or erosion. We could reduce demand for transportation fuels dramatically through other lifestyle changes.

Appendix:**Video Resources:**

What is cellulose and how is it used to make ethanol? (Also accessible from the educational materials page on our website.) - A basic, three-minute video that explains the physical properties of cellulose and how it is broken down into smaller molecules of glucose, which can be fermented into ethanol.

<http://www.vimeo.com/10378252>

Converting Biomass to Liquid Fuels - Excellent 5 minute summary of difference between corn and cellulosic ethanol and process currently used to make cellulosic ethanol. Be aware the process discussed here is evolving and may vary from other information sources you read.

http://www.nrel.gov/learning/re_biofuels.html

Fields of Energy - From the Minnesota Department of Agriculture, a free DVD with student hosts. Two short segments show how corn ethanol is made and the research into cellulosic ethanol. These two segments are currently available online.

<http://www.mda.state.mn.us/kids/>

Life Cycle of Fuels - An eight-minute video that serves as a primer to some of climate change impacts and sustainability issues associated with producing and using biofuels and fossil fuels. <https://vimeo.com/166055834>

Text Resources:

Growing Fuel: the Wrong Way, the Right Way. National Geographic. October 2007. 212(4) pg 38-59. - Provides an overview of different ways to make ethanol and provides some life cycle assessment data. Be aware the results of life cycle analyses varies by methodology. The data provided in this article is older than that from the classroom activity, but the fundamentals still apply.

<http://ngm.nationalgeographic.com/2007/10/biofuels/biofuels-text>

Biofuels: An important part of a low-carbon diet. November 2007. P Monahan, Union of Concerned Scientists "Catalyst" publication. Vol 7(2). - Nice overview comparing the carbon contributions of gasoline, ethanol and other possible transportation fuels. Introduces the concept of a life cycle assessment.

<http://www.ucsusa.org/clean-vehicles/better-biofuels/biofuels-low-carbon-diet#.V1GJZecrKX0>

Follow-up resources:

These are all primary source articles by authors who conduct various types of life cycle

analyses of biofuels. University library permissions may be needed to access full text articles.

Fargione, J., J. Hill, et al. 2008. "Land clearing and the biofuel carbon debt." *Science* 319(5867):1235-1238. - Land use for the production of biofuels can have a significant impact on global CO₂ emissions and corresponding climate change. The authors of this semi-technical article describe the variation in this effect and detail a global set of biofuel production cases. Of particular interest is a bar graph of nine different biofuel/land use systems and the years needed to repay the corresponding carbon debt for their use. This article is scientifically dense and is likely best for advanced high school or undergraduate students.

Field, C. B., J. E. Campbell, et al. 2008. "Biomass energy: the scale of the potential resource." *Trends in Ecology & Evolution* 23(2): 65-72. - For those interested in the food versus fuels debate, this scientific article looks at the global base of abandoned cropland and the corresponding productivity of these areas. This article is scientifically dense and is likely best for advanced high school students.

Hill, J., E. Nelson, et al. 2006. "Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels." *PNAS* 103(30): 4. What are the net energy balances, and the energy inputs and outputs for biofuels? - This article details a life-cycle analysis of both corn grain ethanol and soybean biodiesel biofuels. While this article is technical, with some guidance, it should be understandable by high school students.

Hill, J., S. Polasky, et al. 2009. "Climate change and health costs of air emissions from biofuels and gasoline." *PNAS* 106(6): 2077-82. - Source of graph in figure 5.

National Renewable Energy Lab. 2006. *From Biomass to Biofuels*. - Source of graph in figure 4.

Standards:

AAAS PROJECT 2061 (1993):

3C - The Nature of Technology: Issues in Technology

4D - The Physical Setting: Structure of Matter

4E - The Physical Setting: Energy Transformations

5E - The Living Environment: Flow of Matter and Energy

8A - The Designed World: Agriculture

8C - The Designed World: Energy Sources and Use

11A - Common Themes: Systems



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U.S. DEPARTMENT OF
ENERGY

Thinking About Plants as Transportation Fuel

What have you heard about biofuels, like ethanol, for cars -- are they a good alternative?

Which is a better fuel -- gasoline or ethanol? For each of the criteria below, put a check under what you believe is the best answer.

	Gasoline	Ethanol
Energy per gallon/Miles per gallon		
Energy required to produce a gallon		
Carbon dioxide (CO ₂) emissions		
For the environment		
Amount available		

To create ethanol, sugars in plant biomass (the leaves, stems, and other plant parts) are harvested and converted into fuel (C₂H₅OH).

Based on what you know, check the statement(s) with which you agree.

CO₂ is released when ethanol is produced from plant biomass.

Creating ethanol from plant biomass is carbon neutral*.

Creating ethanol from plant biomass contributes to climate change.

Create a drawing or cycle that explains the production of ethanol from plant biomass. Show the movement of carbon or carbon dioxide from location to location as best you can.

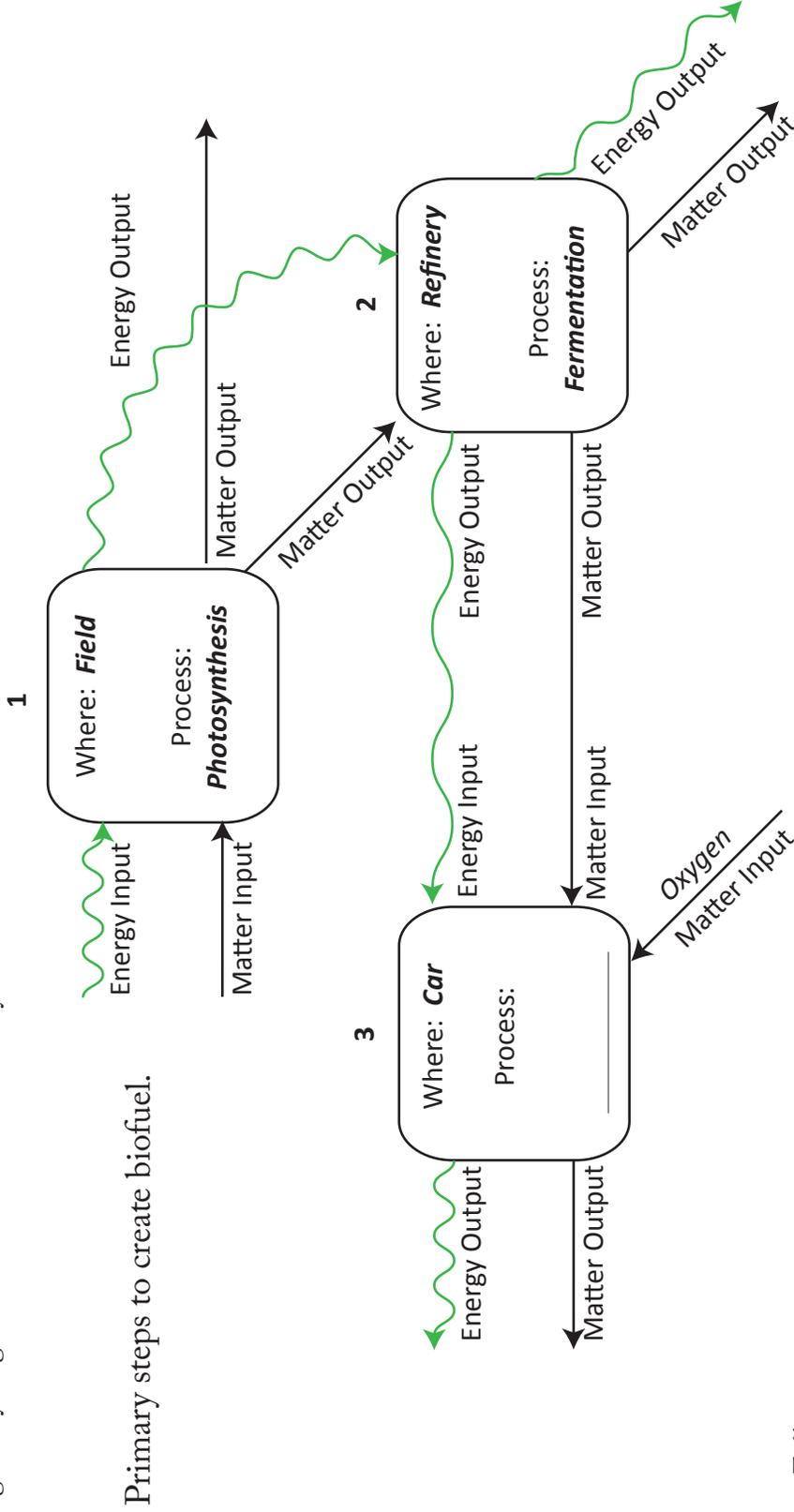
** Carbon-neutral implies that the amount of carbon dioxide released into the atmosphere equals the amount taken up by plants during photosynthesis.*

Discuss your answers with others. Were there any questions that were hard to answer? Why? What additional information would you need to decide? Take notes on agreements, disagreements and questions that remain after your discussion.

	Agreements, Disagreements, and Questions
Energy per gallon/Miles per gallon	
Energy Required to produce a gallon	
Carbon dioxide emissions	
For environment	
Amount available	
Creating ethanol from plant biomass is carbon neutral	
Creating ethanol from plant biomass contributes to global warming	
CO₂ is released to produce ethanol from plants	

Life Cycle Assessment Process Tool

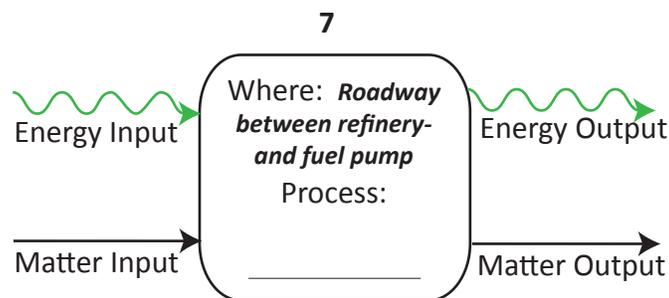
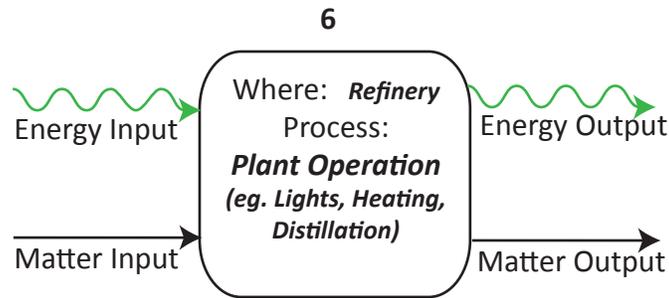
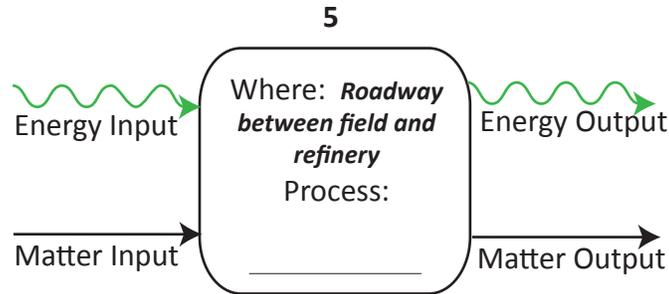
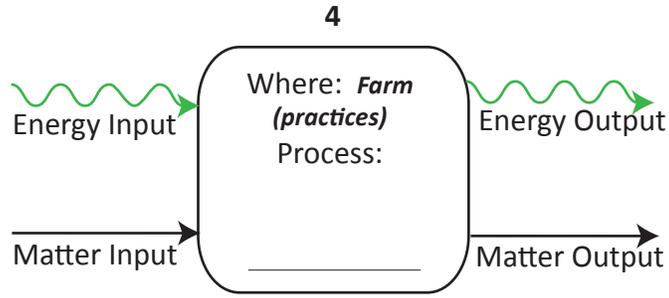
Demonstrate the flow of energy and matter through this system to make ethanol. Enter the correct energy input and output above the wavy lines and matter input and output above the straight lines. Pay attention to stages with more arrows than the others. Determine which inputs and outputs stay in the system and which “escape.” The first page follows the energy from the field to the refinery to your car. The second page shows additional inputs needed to create the fuel. Fill in the “process” occurring at any stage where it is not filled in for you.



Follow-up questions:

1. What is the relationship between the matter output from #3 to the matter input in #1?
2. Does all energy put into #1 make it to the energy output stage of #3? Why or why not?
3. If we are conducting a life cycle assessment for energy or greenhouse gases, like carbon dioxide, why can't we stop at stages 1-3? Why do we need to include stages 4-7 as well?

Additional inputs to create biofuel.



Follow-up questions:

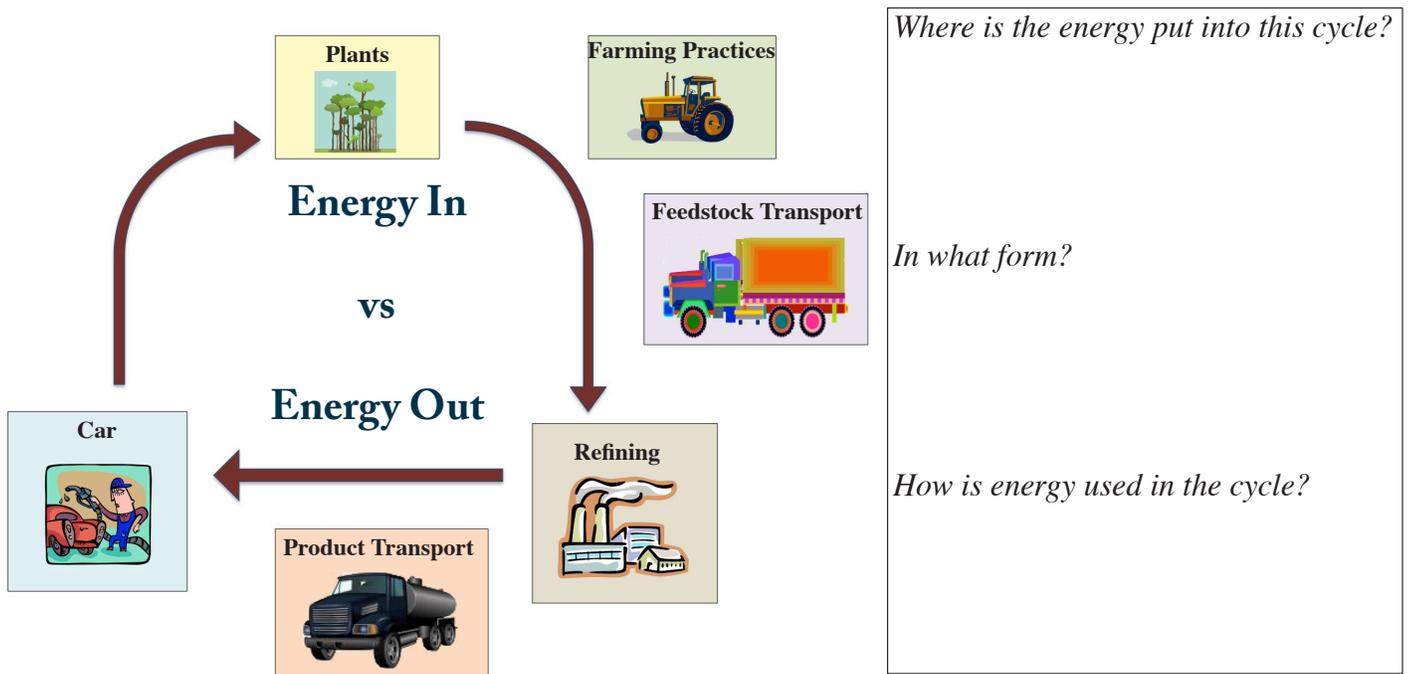
1. Describe how you would determine the net energy gain or loss for ethanol production. Write an equation using only the relevant steps. You can abbreviate EI for Energy Input and EO for Energy Output (eg. EI #1 - EO #7=).

2. How do you think you could best improve the energy efficiency of this process? Reduce the carbon footprint?

Life Cycle Assessment

In order to compare the environmental consequences from using different fuels, scientists conduct what is called a life cycle assessment (LCA). In a bioenergy LCA they look at all of the steps along the way—from planting a crop, to harvesting, to transporting it, to refining to vehicle use. One measurement in an LCA determines the amount of energy used or produced at each step (Figure 1). They also calculate greenhouse gas emissions through the cycle to see, for example, where carbon dioxide is taken in by plants or emitted from combustion (Figure 2).

Figure 1—Life Cycle Assessment of Energy for Ethanol Production and Consumption.



Glossary of select terms for Life Cycle Assessment

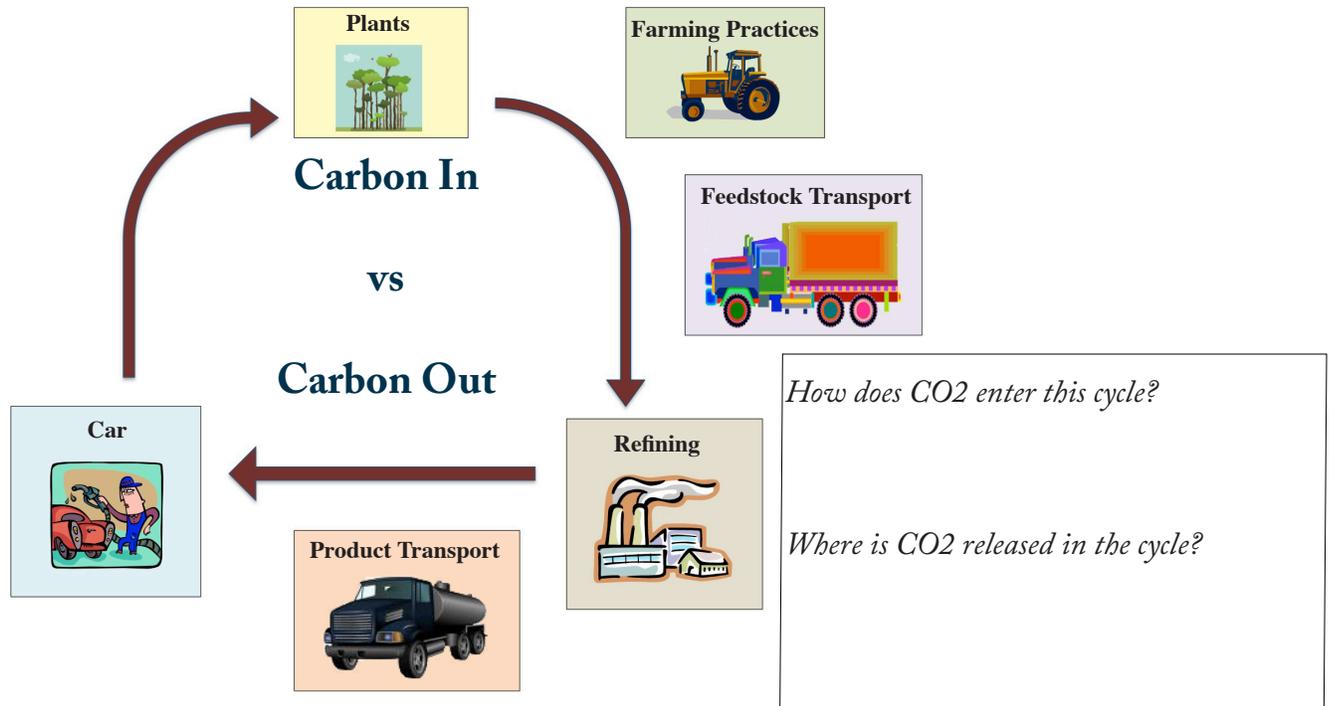
Feedstock—the plants or waste products (corn grain, corn stover, switchgrass, sugar cane, wood chips, etc) used to create biofuels such as ethanol, or other industrial chemicals.

Refining—the process of transforming the plant material into fuel. This may include physical and chemical changes to the plant material, fermentation and distillation.

Sequester—to remove gases from the atmosphere (in our case carbon dioxide) and transform it via photosynthesis in the plant into carbohydrates, which can be stored.

Transport—moving raw materials or finished products from point to point

Figure 2--Life Cycle Assessment of Carbon Dioxide for Ethanol Production and Consumption.



1. *Try your own life cycle assessment.*

Calculating these amounts can be very tricky. There are many steps along the way to measure and/or estimate what is happening. For the chart below, consider only carbon dioxide. Work through the qualitative steps of a life cycle assessment, beginning with planting the crop. Decide if CO₂ is sequestered or released in each of these steps. Explain how or why for each step (photosynthesis, cellular respiration, combustion).

Steps:	Carbon Sequestered or Released?	Form of carbon (from__ to__)	How or why? (Photosynthesis, cellular respiration, combustion)
<i>Planting crop</i>	<i>Released</i>	<i>Gasoline to CO₂</i>	<i>Combustion</i>

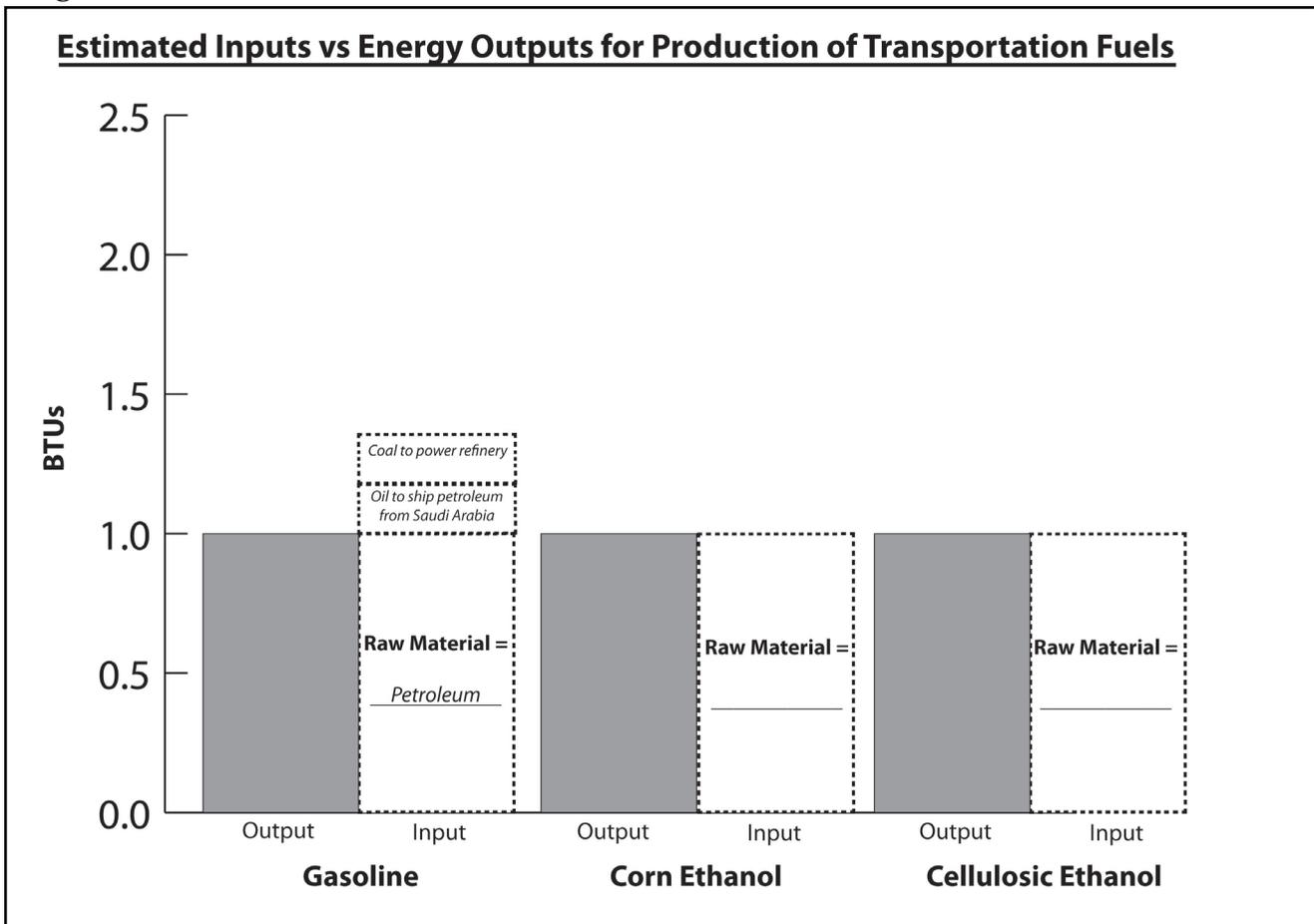
2. In order for ethanol production to be carbon neutral, what would need to happen?

3. Where along the way could you modify the system to reduce the total amount of carbon dioxide released into the atmosphere? What other measurements should be made in a bioenergy life cycle assessment? Are there other choices that could be made that would make the system less damaging to the environment?

Complete the graph.

- First, fill in the blank dashed input bars with the raw material needed to create one BTU of each fuel.
- Second, stack additional energy inputs above the raw material to indicate the energy needs to produce each fuel. Use your list from question 1 for ideas and estimate the amount of energy needed from each source as you add it to the stack. Gasoline is started for you.

Figure 3

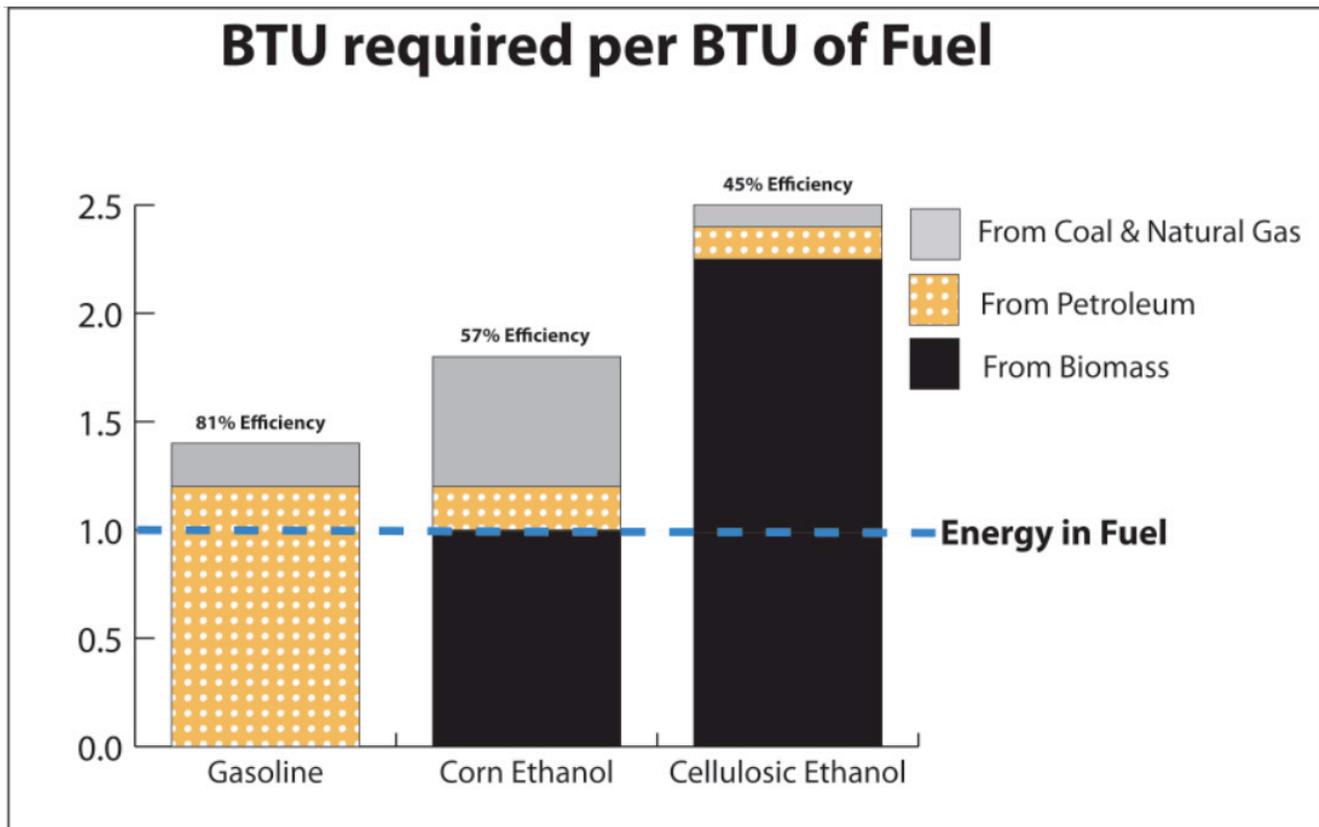


3. Which fuel do you think will require the greatest amount of energy to manufacture? Why?

4. Why is the output bar for one fuel source always lower than the input?

Compare your graph to Figure 4, which was taken from a document from the National Renewable Energy Lab. Take some time to interpret this graph.

Figure 4

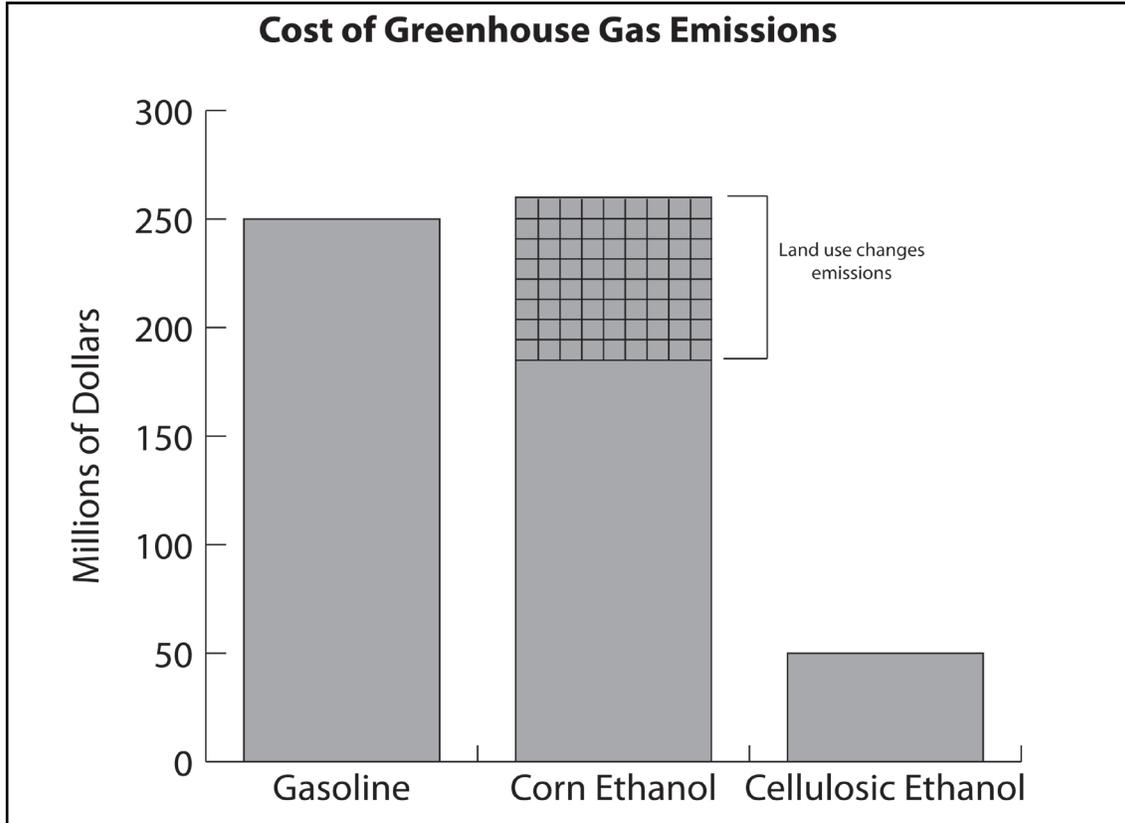


Adapted from NREL 2006. Biomass to biofuels.

1. The dashed line is equivalent to what on figure 3? _____
2. Do the vertical bars represent energy inputs or outputs? _____
3. Which fuel currently requires the most BTUs to produce? _____
4. Which fuel requires the least amount of fossil fuels to produce? _____
5. The efficiency above each bar refers to the amount of energy needed to produce the transportation fuel. Which fuel is most efficient? _____ What percent? _____
6. If gasoline is most efficient, why would we even consider making ethanol from corn or cellulosic biomass? _____

Now take a look at some results of a life cycle assessment of greenhouse gases. Note that estimates of emissions from both corn and cellulosic ethanol are highly variable depending upon where and how the crop is grown, as well as the crop choice for cellulosic ethanol.

Figure 5



Adapted from Hill et al. 2009. PNAS. Production estimate per one billion gallons of fuel to meet US demand. Corn ethanol refinery uses natural gas. Boxed area on corn ethanol indicates emissions estimate if previously unfarmed land is plowed to grow more corn. Cellulosic ethanol refinery uses switchgrass. Dollar amounts were calculated from prices from carbon mitigation costs, carbon market, and social costs.

7. Why is the measurement for corn ethanol almost the same as gasoline?

8. The bar for corn ethanol includes possible changes in land use to grow additional acres of corn. Is this land use change inevitable? Are there alternatives the United States could consider to prevent land use changes?

9. Revisit your choices on page one. Do you still hold the same opinion? Explain which transportation fuel you think is most sustainable. What have you learned in this activity to either change your mind or support your original position? (Write your answer on the back of this page.)