Avoiding Carbon Dioxide Emissions from Burning Fossil Fuels

SPN LESSON #31

TEACHER INFORMATION

LEARNING OUTCOME: After performing stoichiometric calculations for various alkanes that comprise fossil fuel and working with the emissions avoidance component of the school's DAS system, students are able to cite quantitative evidence showing how nonfossil fuel sources help to reduce air pollution by carbon dioxide.

LESSON OVERVIEW: The purpose of this lesson is for students to calculate stoichiometrically the amount of carbon dioxide that would be emitted from burning a mole of various alkanes that comprise fossil fuels. If the energy released from burning a mole of these alkanes is known, then the amount of carbon dioxide emitted per unit of energy produced can be determined. Converting this energy to kilowatt-hours allows calculation of the carbon dioxide emissions that would be avoided by generating electricity with photovoltaic cells or other nonfossil fuel sources instead of burning fossil fuels.

GRADE-LEVEL APPROPRIATENESS: This Level III Physical Setting lesson is intended for use in high school chemistry classrooms.

MATERIALS: Student handout

SAFETY: No special precautions are necessary.

TEACHING THE LESSON: This lesson is an application of mole-mole, mole-mass, and mass-mass problems in chemistry. Students who have learned these basic stoichiometric concepts learn in this lesson to relate these concepts to the environmental problems resulting from burning fossil fuels.

ACCEPTABLE RESPONSES FOR DEVELOP YOUR UNDERSTANDING SECTION:

Write balanced equations for burning ethane (C_2H_6) and propane (C_3H_8).

_2_ C_2H_6 + _7_ $O_2 \rightarrow$ _4_ CO_2 + _6_ H_2O.

_1_ C_3H_8 + _5_ $O_2 \rightarrow$ _3_ CO_2 + _4_ H_2O.

The general formula for an alkane is C_nH_{2n+2}, where *n* is an integer. Write a chemical reaction for the burning of *any* alkane.

_2_ C_nH_{2n+2} + _(3n +1)_ $O_2 \rightarrow$ _2n_ CO_2 + _(2n+2)_ H_2O.

1. How many moles of carbon dioxide are released when a mole of methane is burned?
one

2. How many moles of carbon dioxide are released when a mole of ethane is burned?
two

3. How many moles of carbon dioxide are released when a mole of propane is burned?
three

4. How many moles of carbon dioxide are released when a mole of any alkane of formula C_nH_{2n+2} is burned?
n

5. At the rate of generating 6.5 kWh and avoiding emission of 3 kilograms of carbon dioxide per day, how many kilograms of carbon dioxide will a 2 kW photovoltaic system eliminate in a year?

3 kg/day x 365 days/year = 1095 kg/year, which is just a little over a tonne per year. (One "tonne" is a so-called "metric ton," 1000 kg.)

6. In 1990 the production of carbon dioxide from burning fossil fuel in the U.S. was 5.0×10^9 tonnes (one tonne = 1000 kg). Projections indicate that unless practices are changed, this will rise to 6.5×10^9 tonnes by the year 2020. The Kyoto Protocol calls for maintenance of carbon dioxide at 1990 levels in developed countries. How many 2 kW photovoltaic systems generating 6.5 kWh of electricity per day would be needed to achieve this goal in the United States?

If each 2 kW system eliminated a tonne of carbon dioxide per year, then 1536 million systems would eliminate the 1536 million tonnes of carbon dioxide expected in 2020 above the emission of 4960 million tonnes in 1990. This figure—1536 million—represents approximately five such photovoltaic systems per American!

In actuality, the number of 2 kW photovoltaic systems needed to restore expected worldwide carbon dioxide emissions in 2020 to 1990 levels would be less than this, for at least *two reasons: 1) photovoltaic systems placed at more southern latitudes and in sunnier climates would generate more than 6.5 kWh per day; 2) most fossil-fueled electric generation comes from coal, which produces more carbon dioxide per kWh generated than the fuels in this activity, which correspond to oil and natural gas.*

7. How many grams of carbon dioxide would the 2 kW photovoltaic system avoid per day if the same 6.5 kWh per day were provided by burning ethane (again, by converting the heat produced to electricity with only 40% efficiency)?
6.5 kWh x (1 mol C_2H_6 /.4331 kWh) x (2 mol CO_2 /1 mol C_2H_6) x (44 g CO_2 /1 mol CO_2)/0.4 = 3302 grams CO_2.

8. How many grams of carbon dioxide would the 2 kW photovoltaic system avoid per day if the same 6.5 kWh per day were provided by burning propane (again, by converting the heat produced to electricity with only 40% efficiency)?
6.5 kWh x (1 mol C_3H_8 /.6163 kWh) x (3 mol CO_2 /1 mol C_3H_8) x (44 g CO_2 /1 mol CO_2)/0.4 = 3480 grams CO_2.

9. How does the avoidance of carbon dioxide emissions for ethane and propane compare with that for methane? What do you suggest that would explain why this is so?
Suggest why it is more environmentally advantageous to burn natural gas than other fossil fuels.

As the number of carbon atoms in a fuel molecule increases, the number of grams of carbon dioxide emitted per gram of fuel increases, while the energy yield per gram of fuel decreases. Thus, the number of grams of carbon dioxide emitted per energy unit increases as the number of carbon atoms per fuel molecule increases, and methane (the principal constituent of natural gas) is the alkane with the lowest carbon dioxide emission per energy unit. In addition to emitting less carbon dioxide, natural gas is also free of sulfur, whose oxides form another type of pollution.

ADDITIONAL SUPPORT FOR TEACHERS

SOURCE FOR THIS ACTIVITY: This lesson is not adapted.

BACKGROUND INFORMATION: Assuming all the carbon atoms in the fossil fuel end up in carbon dioxide molecules after the fuel is burned, the number of moles of carbon dioxide produced by burning one mole of fuel equals the number of carbon atoms in a molecule of the fuel. This can be seen from the above balanced chemical reaction for the burning of any alkane. Since the mass of a mole of fuel is $12n + 2n + 2 = 14n + 2$, where n is the number of carbon atoms per molecule, the ratio of the number of grams of carbon dioxide to the number of grams of fuel is $44n/(14n + 2)$, which increases slightly as n increases to a limit of 22/7 for very large n.

While the ratio of carbon dioxide mass to fuel mass increases as the number of carbon atoms per molecule increases, the energy released per gram of fuel burned decreases, as is seen in the following table:

Number of C atoms	Energy per mole (kJ/mol)	Energy per gram (kJ/g)	#g CO_2 per gram	#g CO_2 per kJ
1	890	55.6	2.75	.0494
2	1559	52.0	2.93	.0564
3	2219	50.4	3.00	.0595
4	Data not available			
5	3508	48.7	3.06	.0627
6	4161	48.4	3.07	.0634
7	4809	48.1	3.08	.0640
8	5448	47.8	3.09	.0646
9	Data not available			
10	6734	47.4	3.10	.0653

Thus the carbon dioxide emissions per unit of energy increase as the number of carbon atoms per molecule increases. From the carbon dioxide emissions point of view, the least offending fossil fuel is methane, the primary constituent of natural gas.

The number of grams of carbon dioxide is *divided* by the efficiency of conversion to electricity because

Efficiency = Electricity Output/Thermal Energy Input. So

Thermal Energy Input = Electricity Output/Efficiency and

6.5 kWh/.4 = 16.25 kWh of thermal energy are required to produce 6.5 kWh of electric energy.

REFERENCES FOR BACKGROUND INFORMATION

www.eia.doe.gov/oiaf/9998rpt/carbon.html
http://unfccc.int/resource/docs/cop4/11a02.pdf
Gabriela Martin and Mary O'Toole, "Chicago's Solar-Powered Schools," *Solar Today* (Nov./Dec. 2002).

LINKS TO MST LEARNING STANDARDS AND CORE CURRICULA: 1: M3.1, S1.1; 6: 1, 2.2; 7: 1.2, 2; 4: 3.2c, 3.3a,c,e, 4.1a

Standard 1—Analysis, Inquiry, and Design: Students will use mathematical analysis, scientific inquiry, and engineering design, as appropriate, to pose questions, seek answers, and develop solutions.

Mathematics Key Idea 3: Critical thinking skills are used in the solution of mathematics problems.

M3.1: Apply algebraic and geometric concepts and skills to the solution of problems.

Science Key Idea 1: The central purpose of scientific inquiry is to develop explanations of natural phenomena in a continuing, creative process.

S1.1: Elaborate on basic scientific and personal explanations of natural phenomena, and develop extended visual models and mathematical formulations to represent thinking.

Standard 6—Interconnectedness: Common Themes: Students will understand the relationships and common themes that connect mathematics, science, and technology and apply the themes to these and other areas of learning.

Key Idea 1: Through systems thinking, people can recognize the commonalities that exist among all systems and how parts of a system interrelate and combine to perform specific functions.

Key Idea 2: Models are simplified representations of objects, structures, or systems used in analysis, explanation, interpretation, or design.

2.2: Collect information about the behavior of a system and use modeling tools to represent the operation of the system.

Standard 7—Interdisciplinary Problem Solving: Students will apply the knowledge and thinking skills of mathematics, science, and technology to address real-life problems and make informed decisions.

Key Idea 1: The knowledge and skills of mathematics, science, and technology are used together to make informed decisions and solve problems, especially those relating to issues of science/technology/society, consumer decision making, design, and inquiry into phenomena.

1.2: Analyze and quantify consumer product data, understand environmental and economic impacts, develop a method for judging the value and efficacy of competing products, and discuss cost-benefit and risk-benefit trade-offs made in arriving at the optimal choice.

Key Idea 2: Solving interdisciplinary problems involves a variety of skills and strategies, including effective work habits, gathering and processing information; generating and analyzing ideas; realizing ideas; making connections among the common themes of mathematics, science, and technology; and presenting results.

Standard 4—The Physical Setting: Students will understand and apply scientific concepts, principles, and theories pertaining to the physical setting and living environment and recognize the historical development of ideas in science.

Key Idea 3: Matter is made up of particles whose properties determine the observable characteristics of matter and its reactivity.

3.2: Use atomic and molecular models to explain common chemical reactions.

3.2c: Types of organic reactions include addition, substitution, polymerization, esterification, fermentation, saponification, and combustion.

3.3: Apply the principle of conservation of mass to chemical reactions.

3.3a: In all chemical reactions there is a conservation of mass, energy, and charge.

3.3c: A balanced chemical equation represents conservation of atoms. The coefficients in a balanced chemical equation can be used to determine mole ratios in the reaction.

3.3e: The formula mass of a substance is the sum of the atomic masses of its atoms. The molar mass (gram-formula mass) of a substance equals one mole of that substance.

Key Idea 4: Energy exists in many forms, and when these forms change energy is conserved.

4.1: Observe and describe transmission of various forms of energy.

4.1a: Energy can exist in different forms, such as chemical, electrical, electromagnetic, thermal, mechanical, nuclear.

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Should you have questions about this activity or suggestions for improvement, please contact Bill Peruzzi at billperuz@aol.com

(STUDENT HANDOUT SECTION FOLLOWS)

Name ___________________________________

Date ____________________________________

Avoiding Carbon Dioxide Emissions from Burning Fossil Fuels

Fossils can be defined as any indications of prehistoric life. Many of the fossils that are known are believed to have formed when material that later became rock was deposited along with the remains of organisms that were once alive. Fossil fuels (coal, oil, and natural gas) are so named because they were similarly formed millions of years ago from the organisms themselves.

Fossil fuels have brought extraordinary convenience to our lives in the last hundred years or so. But we are burning them at a rate far greater than the rate at which they form. Because of this, we will eventually run out of fossil fuels; they are said to be *nonrenewable*.

But that is only one problem with the burning of fossil fuels. Because fossil fuels are made from once living things, they contain carbon. When carbon is burned, it chemically combines with oxygen in the air, forming carbon dioxide. In the atmosphere carbon dioxide has the ability to absorb and reradiate infrared radiation. The Earth radiates as infrared radiation the energy it absorbs from the Sun; if this did not happen, the Earth's temperature would continually increase. When carbon dioxide in the atmosphere absorbs and reradiates infrared radiation, half of it comes back to Earth and makes the Earth warmer. If the atmosphere contained no carbon dioxide at all, the Earth would be too cold for comfortable living. But we are now in danger of putting so much carbon dioxide into the air that climate patterns that have sustained life on Earth through the course of human history will be disrupted. In the year 1997 alone, burning fossil fuels released 5422 million tonnes of carbon dioxide into the atmosphere.

DEVELOP YOUR UNDERSTANDING

Fossil fuels are made up of hydrocarbons, chiefly *alkanes*, in which hydrogen atoms are bonded to carbon atoms joined together in open chains that have branches. The simplest alkane is methane, the primary constituent of natural gas. Its molecules consist of one carbon atom surrounded by four hydrogen atoms. As is the case with burning all hydrocarbons, the products of burning methane in the air are water and carbon dioxide. The balanced equation for this chemical reaction is

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O.$$

___ C_3H_8 + ___ $O_2 \rightarrow$ ___ CO_2 + ___ H_2O.

The general formula for an alkane is C_nH_{2n+2}, where n is an integer. Write a chemical reaction for the burning of *any* alkane.

___ C_nH_{2n+2} + ___ $O_2 \rightarrow$ ___ CO_2 + ___ H_2O.

From the balanced chemical reaction for the burning of any alkane, you can determine the number of moles of carbon dioxide released for every mole of the alkane that is burned.

1. How many moles of carbon dioxide are released when a mole of methane is burned?

2. How many moles of carbon dioxide are released when a mole of ethane is burned?

3. How many moles of carbon dioxide are released when a mole of propane is burned?

4. How many moles of carbon dioxide are released when a mole of any alkane of formula C_nH_{2n+2} is burned?

Photovoltaic cells and other nonfossil sources of energy reduce the emissions of carbon dioxide into the atmosphere. We can find out how much by knowing the energy released from burning a mole of a given alkane. These amounts are given in kJ (kilojoules) per mole. For the first three alkanes, these energies are as follows:

alkane	energy released (kJ/mol)
methane	889.89
ethane	1559.09
propane	2218.84

A kilojoule is enough energy to provide a kilowatt of power for one second:

1 kJ = 1 kW·s.

Write below balanced equations for burning ethane (C_2H_6) and propane (C_3H_8).

___ C_2H_6 + ___ O_2 → ___ CO_2 + ___ H_2O.

Since an hour contains 3600 seconds, a kilojoule is 1/3600 of a kilowatt-hour (kWh). Thus the energy (in kWh) released by burning a mole of the first three alkanes is

alkane	act. energy released (kWh/mol)
methane	.2472
ethane	.4331
propane	.6163

Suppose that a typical daily output of the 2 kW photovoltaic system is 6.5 kWh. At this rate, the 2 kW photovoltaic system eliminates
6.5 kWh x (1 mol CH_4/.2472 kWh) x (1 mol CO_2/1 mol CH_4) x (44 g CO_2/1 mol CO_2) =

1157 g CO_2 per day,

which would have been emitted if natural gas (methane) had been burned instead. Actually, since the heat from burning natural gas is converted to electricity at only 40% efficiency, the carbon dioxide avoidance is even greater by a factor of 1/0.4 = 2.5, thus bringing it to 2893 grams per day, which is almost 3 kilograms.

5. At the rate of generating 6.5 kWh and avoiding emission of 3 kilograms of carbon dioxide per day, how many kilograms of carbon dioxide will a 2 kW photovoltaic system eliminate in a year?

6. In 1990 the production of carbon dioxide from burning fossil fuel in the U.S. was 5.0×10^9 tonnes (one tonne = 1000 kg). Projections indicate that unless practices are changed, this will rise to 6.5×10^9 tonnes by the year 2020. The Kyoto Protocol calls for maintenance of carbon dioxide at 1990 levels in developed countries. How many 2 kW photovoltaic systems generating 6.5 kWh of electricity per day would be needed to achieve this goal in the United States?

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8. How many grams of carbon dioxide would the 2 kW photovoltaic system avoid per day if the same 6.5 kWh per day were provided by burning propane (again, by converting the heat produced to electricity with only 40% efficiency)?

9. How does the avoidance of carbon dioxide emissions for ethane and propane compare with that for methane?

What do you suggest that would explain why this is so?

Suggest why it is more environmentally advantageous to burn natural gas than other fossil fuels.