The Energy Efficiency of Heating Water | A Lab Investigation

Summary

Students use a Bunsen burner, microwave oven, and hot plate to determine which instrument heats water most efficiently. Students perform detailed calculations to support their conclusions.

Objective

Students will use observations to calculate the energy efficiency of various heating methods.

Safety

- Be sure you and the students wear properly fitting goggles.
- Review safe use of Bunsen burners or hot plates. Caution students about handling hot water to avoid scalds or burns.
- Methane (natural gas) is flammable. It can be explosive if mixed with air in certain proportions. Avoid any sparks or flames when collecting the gas. Methane is toxic by inhalation. Work in a well-ventilated area.

Materials for Each Group

- 1 Bunsen burner
- 1 hot plate
- 1 one-meter hose sections of tubing
- 1 tub or bucket for holding water
- 1 stopwatch or clock with a second hand
- 1 2-L soda bottle (clear with label removed)
- 1 400-mL beaker
- 1 alcohol thermometer
- 1 ring stand support with ring
- 1 pair of beaker tongs

Materials for the Whole Class

- 1 microwave oven (shared by all groups)
- A variety of volumetric containers, such as large graduated cylinders for each group

Time Required

Two to three class periods, approximately 45–50 minutes each.

Lab Tips

It may be difficult for some students to come up with a satisfactory scheme for collecting and measuring the amount of methane collected from the gas outlet. Lend appropriate hints and tips as required. If your lab doesn't have a typical standard gas system piped in permanently, consider using portable gas burners, alcohol lamps, or whatever other alternative system you generally use. Also, consider using portable electric immersion heaters in the place of hot plates. They are much more efficient and at $10 per heater, much less expensive.

If presented as a "lab challenge" this basic investigation could be adapted as a lab practical exam to test how students are able to apply what they have learned. You could vary the complexity of the task by adjusting the amount of information you provide (such as the enthalpy of combustion for methane). This investigation also provides an opportunity for considering the total environmental cost involved in a simple lab procedure.

Pre-Lab Discussion

Make sure students are familiar with the proper operation of Bunsen burners, hot plates, and microwaves. You may direct students to read the procedure and make up appropriate data tables before they go to the lab. Their data tables can be their "passport" to begin the investigation.

Incorporating into the Curriculum

This investigation could be incorporated into a unit on stoichometry, chemical changes, or thermochemistry.

TEACHER'S KEY

Analyzing Evidence

Sample data:

200 g water, $\Delta T = 50.5\,°C$ (16.0 °C to 66.5 °C)

Combustion of 4.86 L of methane, $\Delta H = -802.3$ kJ/mol CH_4

698-watt electric hot plate

1000-watt microwave

Electricity: 10.56¢ per kilowatt-hour

Natural gas: $11.80 per thousand cubic feet

Analyzing Part A

From sample data

$$\text{Energy absorbed by water (J)} = 200\text{ g} \times 50.5\,°\text{C}) \times \left(\frac{4.18\text{ J}}{\text{g}\cdot°\text{C}}\right) = 42.2 \times 10^3\text{ J}$$

$$\begin{array}{c}\text{Energy released}\\ \text{by burning}\\ \text{natural gas (J)}\end{array} = 245\text{ s} \times 0.0198\text{ L/s} \times \left(\frac{1\text{ mol gas}}{22.4\text{ L}}\right) \times \left(\frac{802 \times 10^3}{1\text{ mol gas}}\right) = 174 \times 10^3\text{ J}$$

$$\%\text{ Efficiency} = \left(\frac{42.2 \times 10^3\text{ J}}{174 \times 10^3\text{ J}}\right)100\% = 24\%$$

Analyzing Part B

$$\text{Energy absorbed by water (J)} = 200\text{ g} \times 50.5\,°\text{C}) \times \left(\frac{4.18\text{ J}}{\text{g}\cdot°\text{C}}\right) = 42.2 \times 10^3\text{ J}$$

$$\text{Energy released by hot plate (J)} = 698\text{ watt} \times 378\text{s} \times \left(\frac{1\text{ J/s}}{\text{watt}}\right) = 264 \times 10^3\text{ J}$$

$$\%\text{ Efficiency} = \left(\frac{42.2 \times 10^3\text{ J}}{264 \times 10^3\text{ J}}\right)100\% = 16\%$$

Analyzing Part C

Energy absorbed by water (J) = 200 g × 50.5 ° C) × $\left(\frac{4.18\ J}{g \cdot {}^\circ C}\right)$ *=* $42.2 \times 10^3\ J$

Energy released by microwave (J) = 698 watt × 378s × $\left(\frac{1\ J/s}{watt}\right)$ *=* $264 \times 10^3\ J$

% Efficiency = $\left(\frac{42.2 \times 10^3\ J}{264 \times 10^3\ J}\right)$ *= 16%*

Sample Data

Heat source	Energy released (kJ)	Energy absorbed (kJ)	Efficiency	Time (sec)	Cost (¢)	Savings*
Bunsen burner	174	42.2	24%	245	0.203	0.571¢
Hot plate	264	42.2	16%	378	0.774	-
Microwave	62	42.2	68%	62	0.181	0.593¢

**as compared to the most expensive method tested.*

Interpreting Evidence

1. When you have calculated the efficiency for heating by each method, record your results along with the rest of the class on the board in the front of the classroom, or as your teacher directs. Calculate the average efficiency for each of the methods and discuss the precision in the range of results of the data from the various lab groups.

   Discuss any result that differs significantly from the class average, and if time allows, repeat the experiment to improve the precision.

   This investigation typically yields consistent results. The discussion of results that differ from the average can lead to an appreciation of care and accuracy in doing lab investigations. Consider having students redo their investigation after a discussion of ways to control variability.

2. Compare the results of the three methods of heating. Which was the most efficient, and which was the least efficient? Did the results follow what you expected?

   The microwave method is likely to be the most efficient method of heating, followed by the Bunsen burner and then the hot plate. This is reasonable because the microwaves heat by directly increasing the motion of the water molecules, while the other methods have a more indirect transfer, which can be subject to inefficient heating.

Reflecting on the Investigation

1. Use your household electricity and natural gas bills to calculate the cost in dollars for each part of this investigation. Calculate the cost for heating a sample of water by 10 °C for each type of heating. If natural gas is not available in your community, use the national average price or substitute the cost of propane gas (an alternative fuel to natural gas).

   Although the cost in dollars is not a perfect reflection of the total cost to the environment., it does reflect how difficult it is to bring the energy source to market. Which energy source was the most expensive? Which was the least expensive?

   Using the data from the experiment above, we can divide the cost to raise the temperature of 200 g of water by 50.5 °C to get the cost per degree. Multiplying this result by 10 °C gives the desired cost for the 10 °C rise. It is about equal in expense to heat with cheaper natural gas in an inefficient Bunsen burner, as it is to use more expensive electricity in a relatively efficient microwave oven. The inefficient hot plate was much more expensive.

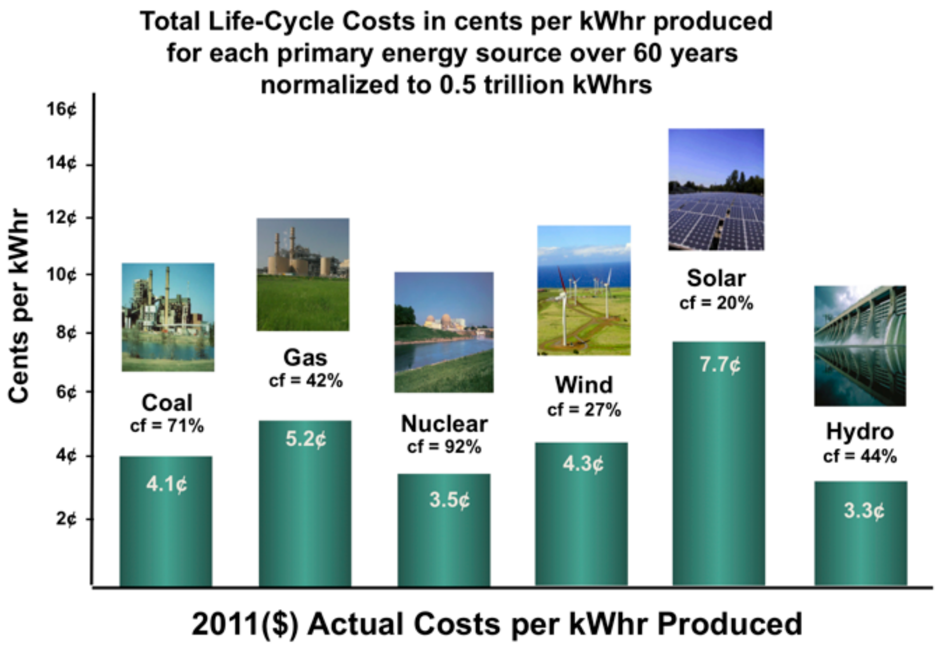
Heat source	Exp ΔT	Cost (¢)	Cost/10 °C
Bunsen burner	50.5 °C	0.203¢	0.040¢
Hot plate	50.5 °C	0.77¢	0.153¢
Microwave	50.5 °C	0.181¢	0.035¢

2. There are many ways to generate electricity and produce natural gas. Some require less energy to produce, and some give off less pollution. Using the Internet and other resources, investigate which power source tends to require less energy to produce and contributes less total pollution to the environment.

   This is obviously a huge question. There is an interesting discussion of this issue at the Canadian website www.iclei.org.

   "All energy use has some negative impact on the environment. Burning fossil fuels such as coal and oil produces emissions of greenhouse and acid gases, which result in global warming and acid rain, respectively. Fossil fuels are also responsible for urban air pollution and its associated health hazards. Nuclear power plants expose the environment to low levels of radiation during many stages of the nuclear fuel cycle, and also pose risks of nuclear accidents. Storage of spent nuclear fuel continues to be a problem. Even renewable technologies using energy from the sun have some negative impacts on the environment. Hydroelectric dams, for example, can flood vast areas, and damage aquatic ecosystems."

Below is an example of one analysis of total cost for energy production. Note: in this analysis "costs do not include electrical grid upgrade, transportation issues, connectivity of renewables, and buffering of their intermittency by rapid cycling of fossil fuel plants as presently practiced in this country, and externalities such as any carbon-tax, pollution, and health care costs associated with energy production and use. Also, these costs are not levelized but are actual direct costs."



Source: http://forbes.com

3. Using the information you collected regarding efficiency, dollar costs, and environmental costs, make a recommendation for how best to minimize the energy used to heat substances in your school laboratory.

   Students can make suggestions based on your lab results. Students will likely suggest the most efficient heating method that was the lowest cost. A more advanced response will include the "total cost" of energy sources.

Post-Lab Discussion

- Based on the above data, if you lowered the temperature of your 50-gallon hot water tank from 99 °F to 90 °F you would save approximately 20% on the cost of heating your water.
- Heating of larger volumes of water (1 L) with a microwave has been found to be more efficient, about 80% compared to the 68% found for 200 mL of water.
- Heating 1-L volumes with a source that submerses the heating coils in the water, like an electric kettle, has about 90% efficiency.
- The extremely low efficiency of the hot plate is most likely due to the difference in area of the hot plate and the beaker of water. A large percentage of the heat provided by the hot plate is released into the air rather than absorbed by the water.

Extensions

The most complex level of this lab involves the Life Cycle Assessment (LCA) of all the energy costs associated with energy use and production. An LCA considers all the material and energy inputs in a product or process. According to the EPA, LCA is a technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). LCAs can help prevent a narrow outlook on environmental concerns by:

- compiling an inventory of energy and material inputs and environmental releases;
- evaluating the potential impacts associated with identified inputs and releases; and
- interpreting the results to help make a more informed decision.

Students could extend the activity by researching the LCA of fossil fuel sources of energy, means of generating electricity, and other energy sources in the realm of transportation, communication, and leisure.

Additional Resources

- *Introduction to Green Chemistry*. Ryan, M. A.; Tinnesand, M., Eds. American Chemical Society: Washington, DC, 2002.
- Jansen, M. P. "How Efficient is a Laboratory Burner in Heating Water?" *J. Chem. Educ.* 1997, 74, 213–215.

Websites

- National Average Rate of Cost for Electricity
  http://bit.ly/highschoolnrg13

- City of Toronto Energy Efficiency
  http://bit.ly/highschoolnrg14

- U.S. Department of Energy, Efficiency Page
  http://bit.ly/highschoolnrg15

- Forbes Total Cost of Electricity Article
  http://bit.ly/highschoolnrg16