ASPECt
Assessing Students' Progress on the Energy Concept

Engines: AP43-6

High School – Energy and Chemical Reactions

TASK OVERVIEW

Students are provided with a scenario in which an engineer is working on an engine that burns butane as its fuel and is trying to determine the best mixture of butane and oxygen to maximize the amount of energy released when the butane is burned. Students are given data on the total bond energies associated with the products and reactants for a reaction and a graph of the potential energies associated with the reactant molecules, unbonded atoms, and product molecules. After being asked questions about the data and graphs, they are then asked to compare the data and graphs for two reactions in terms of the amount of energy released during each reaction.

TARGETED DCIs, SEPs, AND CCCs

Disciplinary core ideas

- PS1.A-H.4: A stable molecule has less energy than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.
- PS1.B-H.1: Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.

- PS3.C-H.1: When two objects interacting through a field change relative position, the energy stored in the field is changed.

Science & engineering practices

- SEP2-H.3: Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.
- SEP7-H.4: Construct, use, and/or present an oral and written argument or counter-arguments based on data and evidence.

Crosscutting concepts

- CCC5-H.2: Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system.
- CCC2-H.2: Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system.

Related Performance Expectations

- HS-PS1-4. Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy. [*Clarification Statement*: Emphasis is on the idea that a chemical reaction is a system that affects the energy change. Examples of models could include molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved.] [*Assessment Boundary*: Assessment does not include calculating the total bond energy changes during a chemical reaction from the bond energies of reactants and products.]

TASK PERFORMANCE EXPECTATION

Use data and models to illustrate the relationship between the arrangement of atoms in molecules and their associated bond and potential energies. *Write an argument* comparing different reactions and use bond energy data and potential energy diagrams *to explain* which reaction releases more energy.

LINK TO ONLINE VERSION

http://assess.bscs.org/i/test/605

Task

Internal combustion engines, which are used in many cars, transform potential energy into kinetic energy. A group of engineers is working with an engine in which butane reacts with oxygen. They find that different chemical reactions can occur depending on the ratio of butane to oxygen. These different reactions release different amounts of energy. They want to adjust the ratio of butane to oxygen to find the reaction that releases the largest amount of energy.

They start by adjusting the engine so that there is an abundance of oxygen (O_2). When there is an abundance of oxygen, the butane (C_4H_{10}) reacts with the oxygen (O_2) to produce carbon dioxide (CO_2) and water (H_2O) as shown by the chemical reaction below.

Chemical reaction with abundant oxygen

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O$$

To estimate how much energy will be released during this reaction, the engineers sum the bond energies associated with the reactant molecules and product molecules.

		Sum of bond energies (kJ)
Reactant molecules	$2C_4H_{10} + 13O_2$	17,479
Product molecules	$8CO_2 + 10H_2O$	22,044

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1. Based on the information in the table, how much energy is **required** to separate all of the atoms that make up the reactant molecules?
    A. 0 kJ
    B. 17,479 kJ
    C. 22,044 kJ
    D. 4,565 kJ (22,044 kJ - 17,479 kJ)
    E. 39,523 kJ (22,044 kJ + 17,479 kJ)
2. Based on the information in the table, what is the estimated amount of energy **released** by the chemical reaction?
    A. 0 kJ
    B. 17,479 kJ

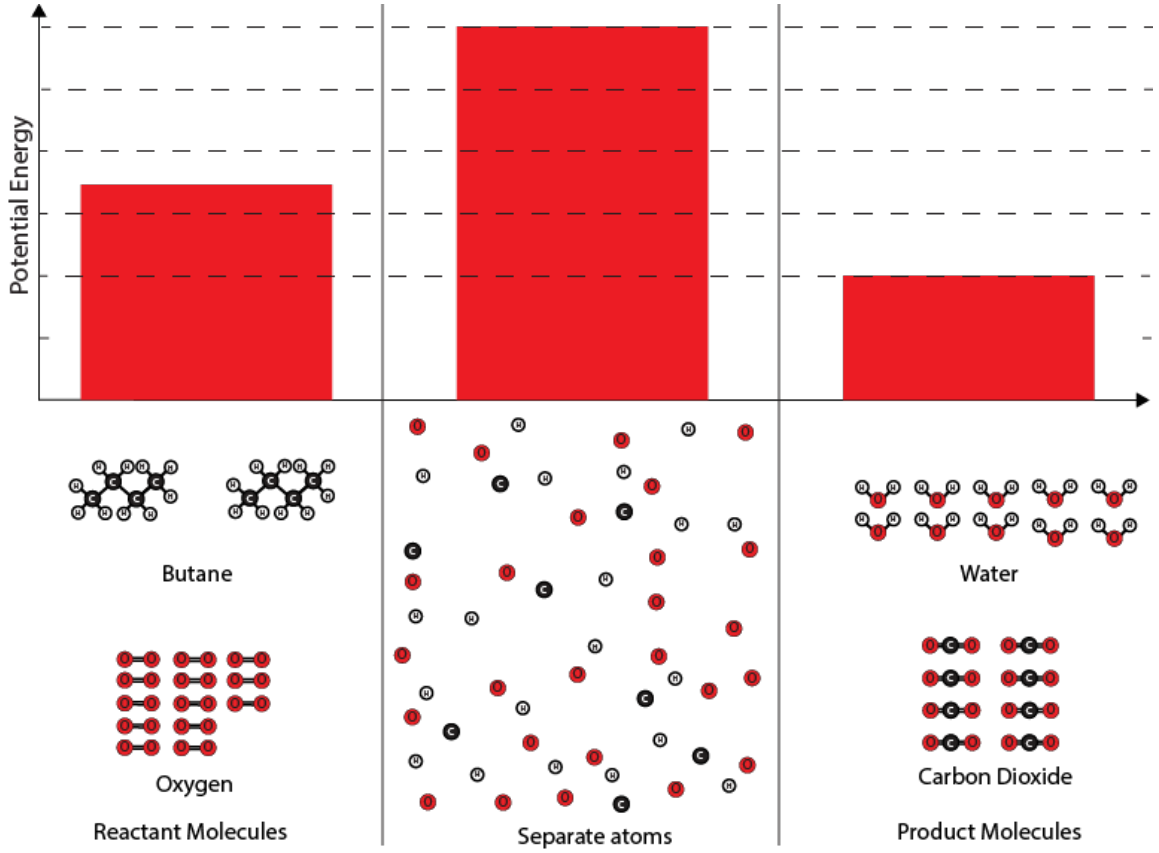
C. 22,044 kJ

D. 4,565 kJ (22,044 kJ - 17,479 kJ)

E. 39,523 kJ (22,044 kJ + 17,479 kJ)

The engineers create a potential energy diagram for the reactant and product molecules. The diagram shows the potential energies of: (1) the reactant molecules (2) the atoms if they were able to be completely separated from one another, and (3) the product molecules.

Potential energy diagram with abundant oxygen



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3. Given that there are attractive forces between atoms that make up the molecules involved in the chemical reaction, why is the potential energy of separated atoms greater than the potential energy of the reactant and product molecules?

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4. How is the bond energy associated with the reactant molecules (17,479 kJ) represented in the potential energy diagram?

A. The bond energy is equal to the height of the bar for the reactant molecules.

B. The bond energy is equal to the height of the bar for the separate atoms.

C. The bond energy is equal to the difference in the heights of the bars for the reactant molecules and the separate atoms.

D. The bond energy is equal to the difference in the heights of the bars for the reactant molecules and the product molecules.

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5. How is the net amount of energy released during the chemical reaction represented in the potential energy diagram?

   A. The net amount of energy released is equal to the height of the bar for the product molecules.

   B. The net amount of energy released is equal to the height of the bar for the separated atoms.

   C. The net amount of energy released is equal to the difference in the heights of the bar for the product molecules and the separated atoms.

   D. The net amount of energy released is equal to the difference in the heights of the bar for the reactant molecules and the product molecules.

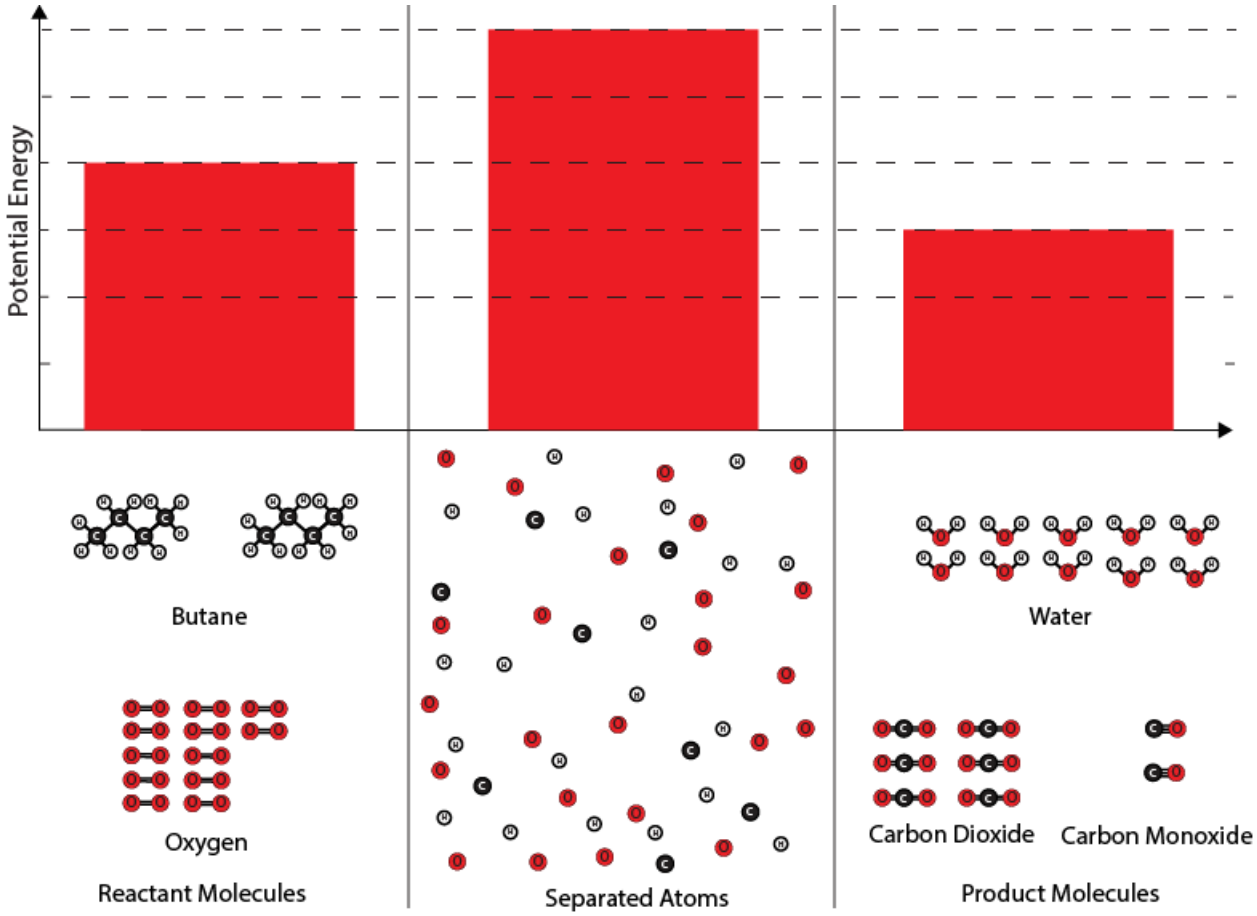
Next, the engineers reduce the amount of oxygen available to the engine. They find that when the amount of oxygen is reduced butane reacts with oxygen to produce carbon dioxide, water, and carbon monoxide (CO). The chemical equation, total bond energies, and potential energy diagram for the chemical reaction in the reduced oxygen environment is shown below.

Chemical reaction with reduced oxygen

$2C_4H_{10} + 12O_2 \rightarrow 6CO_2 + 10H_2O + 2CO$

		Total Bond Energy (kJ)
Reactant molecules	$2C_4H_{10} + 12O_2$	16,984
Product molecules	$6CO_2 + 10H_2O + 2CO$	21,240

Potential energy diagram with reduced oxygen



6. How does the **net amount of energy released** during the chemical reaction in the *reduced* oxygen environment compare to the net amount of energy released during the chemical reaction when oxygen was *abundant*? Support your argument using data from the two tables of bond energies and the two potential energy diagrams.

Alignment to Targeted DCIs, SEPs, and CCCs and Scoring Rubrics

QUESTION 1

Based on the information in the table, how much energy is required to separate all of the atoms that make up the reactant molecules?

A. 0 kJ

B. 17,479 kJ

C. 22,044 kJ

D. 4,565 kJ (22,044 kJ - 17,479 kJ)

E. 39,523 kJ (22,044 kJ + 17,479 kJ)

LEARNING GOAL

Learning Performance

- Using a data table of bond energies associated with reactant and product molecules, identify how much energy is required for a chemical reaction to take place.

Targeted DCIs, SEP, and CCC

- PS1.A-H.4: A stable molecule has less energy than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.

SCORING RUBRIC

Elements of a Correct Response

Categories	Elements
Student selects the correct multiple-choice answer	B. 17,479 kJ

QUESTION 2

Based on the information in the table, what is the estimated amount of energy released by the chemical reaction?

A. 0 kJ

B. 17,479 kJ

C. 22,044 kJ

D. 4,565 kJ (22,044 kJ - 17,479 kJ)

E. 39,523 kJ (22,044 kJ + 17,479 kJ)

LEARNING GOAL

Learning Performance

- Using a data table of bond energies associated with reactant and product molecules, identify how much energy is released by a chemical reaction.

Targeted DCIs, SEP, and CCC

- PS1.B-H.1: Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.
- CCC5-H.2: Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system.

SCORING RUBRIC

Elements of a Correct Response

Categories	Elements
Student selects the correct multiple-choice answer	D. 4,565 kJ (22,044 kJ - 17,479 kJ)

QUESTION 3

Given that there are attractive forces between atoms that make up the molecules involved in the chemical reaction, why is the potential energy of separated atoms greater than the potential energy of the reactant and product molecules?

LEARNING GOAL

Learning Performance

- Construct an explanation for the differences between the potential energy of two configuration of atoms.

Targeted DCIs, SEP, and CCC

- PS1.A-H.4: A stable molecule has less energy than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.
- PS1.B-H.1: Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.
- PS3.C-H.1: When two objects interacting through a field change relative position, the energy stored in the field is changed.
- SEP6-H.3: Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena and solve design problems, taking into account possible unanticipated effects.
- CCC2-H.2: Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system.

SCORING RUBRIC

Ideal Response

A stable molecule has less energy than the same set of atoms separated because the attractive forces between separated atoms work to pull them toward each other. Therefore, chemical reaction systems have more potential energy when the atoms in

the system are separated then when the atoms in the system are bonded together to form molecules.

Elements of a Correct Response

Categories	Elements
Student either states or uses a general science idea	• A molecule has less energy (is more stable) than the same set of atoms separated (i.e., a water molecule has less energy than a set of two hydrogen atom and one oxygen atom). [*molecule less energy than separated atoms]* • When two objects interacting through a force field change relative position, the energy stored in the field is changed (i.e., when the atoms get further apart, there is more potential energy in the system). [*links energy and arrangement of atoms*]
Student uses reasoning to link science ideas to the claim	• The potential energy of separated atoms is greater than the potential energy of the reactant and product molecules because attractive forces work to pull the atoms together which causes the potential energy of the system to increase when the space between atoms increases. OR • The amount of energy in a chemical reaction system depends on how the atoms are arranged because the attractive forces work to pull the atoms together which causes molecules to have less energy/be more stable than the same set of atoms separated.

Sample Student Responses

Student response	Scoring description
"Separate atoms have more of a greater potential because they are not in any chemical reaction yet. The atoms have a greater potential to be used than when they were a molecule."	Score = 0 The response confuses potential energy with the potential to undergo a reaction.

"There is more potential energy because they are more spread out."	Score = 1 The response includes the science idea that the farther apart the atoms are the more potential energy they have.
"The potential energy of separated atoms is greater than that of the reactant and product molecules because when separated, the atoms all are not bound by any other atoms, leaving them in a high energy state that is unstable, which is why they bond together releasing energy, in order to stableize. Energy has to be put in to break the molecules into separate atoms, which is where that energy comes from."	Score = 2 The response includes a well-reasoned explanation.

QUESTION 4

How is the bond energy associated with the reactant molecules (17,479 kJ) represented in the potential energy diagram?

A. The bond energy is equal to the height of the bar for the reactant molecules.

B. The bond energy is equal to the height of the bar for the separated atoms.

C. The bond energy is equal to the difference in the heights of the bars for the reactant molecules and the separated atoms.

D. The bond energy is equal to the difference in the heights of the bars for the reactant molecules and the product molecules.

LEARNING GOAL

Learning Performance

- Identify that bond energy associated with the reactant molecules is the difference in potential energies for the unbonded and bonded atoms.

Targeted DCIs, SEP, and CCC

- PS1.A-H.4: A stable molecule has less energy than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.
- SEP2-H.3: Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

SCORING RUBRIC

Elements of a Correct Response

Student response	Scoring description
Student selects the correct multiple-choice answer	C. The bond energy is equal to the difference in the heights of the bars for the initial configuration and the intermediate configuration.

QUESTION 5

How is the net amount of energy released during the chemical reaction represented in the potential energy diagram?

A. The net amount of energy released is equal to the height of the bar for the product molecules.

B. The net amount of energy released is equal to the height of the bar for the separated atoms.

C. The net amount of energy released is equal to the difference in the heights of the bar for the product molecules and the separated atoms.

D. The net amount of energy released is equal to the difference in the heights of the bar for the reactant molecules and the product molecules.

LEARNING GOAL

Learning Performance

- Identify the net amount of energy released by a chemical reaction is equal to the difference in the potential energy of the reactant and product molecules.

Targeted DCIs, SEP, and CCC

- PS1.A-H.4: A stable molecule has less energy than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.
- PS1.B-H.1: Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.
- SEP2-H.3: Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

SCORING RUBRIC

Elements of a Correct Response

Categories	Elements
Student selects the correct multiple-choice answer	D. The net amount of energy released is equal to the difference in the potential energy of the reactant molecules and the product molecules.

QUESTION 6

How does the net amount of energy released during the chemical reaction in the reduced oxygen environment compare to the net amount of energy released during the chemical reaction when oxygen was abundant? Support your argument using data from both tables of bond energies and both potential energy diagrams.

LEARNING GOAL

Learning Performance

- Analyze data and use models to write an explanation about which chemical reaction releases more energy.

Targeted DCIs, SEP, and CCC

- PS1.B-H.1: Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.
- SEP2-H.3: Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.
- SEP7-H.4: Construct, use, and/or present an oral and written argument or counter-arguments based on data and evidence.
- CCC5-H.2: Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system.

SCORING RUBRIC

Ideal Response

The net release of energy is smaller for the reduced oxygen reaction than the oxygen abundant reaction. The difference in bond energies between the initial and final configurations is larger for the oxygen abundant reaction, so it must be releasing more energy.

Additionally, the graphs show that the difference in heights of the potential energy bars for the initial and final configurations is smaller for the reduced oxygen reaction. This means that the change is energy was smaller for the reduced oxygen reaction and thus less energy was released.

Elements of a Correct Response

Categories	Elements
Student makes a valid claim	• The reduced oxygen reaction ($2C_4H_{10} + 12O_2$) has a smaller net release of energy than the oxygen abundant reaction ($2C_4H_{10} + 13O_2$).
Student cites evidence to support the claim	• The difference in the total bond energy between the products and reactants for the first reaction is 4,565 kJ and the difference in the total bond energy between the products and reactants for the second reaction is 4,008 kJ. • The difference in the heights of the initial and final state bars for the first reaction is one and a half-dashed marks and difference in the heights of the initial and final state bars for the second reaction is one dashed mark. Note: Relative comparisons of the bond energies and bar heights are also accepted. The student does not have to cite actual numbers or bar heights.
Student either states or uses a general science idea	• The amount of energy stored or released by a chemical reaction can be understood by examining the changes in the sum of all bond energies of the product and reactant molecules (i.e., the difference between the energies of the reactant and product molecules is the amount of energy released during the chemical reaction). [*energy & chemical reactions*]
Student uses reasoning to link evidence and/or science ideas to the claim	• Since the reduced oxygen reaction has a smaller difference in total bond energies (or difference in potential energy between the initial and final states), the net reduced oxygen reaction releases less energy than the abundant oxygen reaction.

Sample Student Responses

Student response	Scoring description
"The chemical reaction in reduced oxygen and abunant are similar."	Score = 0 The response does not include the correct claim or an argument to support the claim.
"The net amount of energy released during the chemical reaction in the reduced oxygen environment is less than the net amount of energy released during the chemical reaction when oxygen was abundant. For the reduced oxygen environment, the total bond energy was 16,984 for reactants and 20,992 for products. This amount of energy is less than the total amount of energy with oxygen abundant because for the oxygen abundant, 17,479 was the reactants and 22,044 was the products."	Score = 1 The response includes a claim but compares the bond energies in an incorrect way (i.e., comparing total bond energy of the reactants in one reaction to the total bond energy of the reactants in the other reaction instead of comparing the differences in bond energies between the reactants and products of one reaction to the difference in the other reaction).
"The net amount of energy released during the chemical reaction in the reduced oxygen environment is lower than the net amount of energy released during the chemical reaction when oxygen was abundant. The reactant molecules were around 4,000 kJ higher than the product molecules."	Score = 2 The response includes a claim and implies the science idea, but it does not cite the energy released from the abundant oxygen reaction.
"Less energy is released, as in the second, less oxygenated scenario, 4008 KJ of energy was released, while in the oxygenated scenario, 4565 KJ of energy was released."	Score = 3 The response includes a claim and evidence and uses the science idea, but it does not use reasoning to link them together.
"There is a decrease in net energy released in the reduced oxygen environment. The potential energy difference between the energy diagrams show that there is a decrease in potential energy difference between the reactants and products from the 1st graph to the 2nd. There is also a decrease in the difference of bond energies between reactants and products, meaning that less energy is moved during the reaction."	Score = 4 The response includes all the elements in the rubric.

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