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ANALYSIS OF ENERGY CONCEPTS THROUGH PHET SIMULATION: A CASE STUDY ON SKATE PARK

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Abstract :
This study aims to analyze students' understanding of energy concepts through the PhET simulation in the case of the Skate Park. Energy concepts, including kinetic energy, potential energy, and mechanical energy, often present challenges in physics education, particularly in the context of visual and interactive comprehension. In this study, the PhET "Energy Skate Park" simulation was used to observe energy changes in objects moving along a skate park track at various heights. The study involved high school students conducting experiments using this simulation to understand the basic principles of physics related to energy changes. Data were collected through direct observations and pre-test and post-test quizzes to assess the improvement in students' understanding of energy concepts. The results showed that using the PhET simulation significantly helped students understand the changes between kinetic energy, potential energy, and mechanical energy in a more tangible and visual context. The average post-test score (86.67) demonstrated an increase of 24 points compared to the pre-test score (62.67), with the standard deviation decreasing from 7.91 to 6.05, indicating a more consistent understanding among students. The simulation effectively assisted students in building conceptual schemas through interactive visualization and virtual experiments, aligning with constructivist theory, experiential learning, and multimedia learning theories.The simulation also demonstrated its potential to enhance student engagement and their ability to apply physics concepts to real-life situations.

Keywords: Kinetic energy, Mechanical energy, Potential energy

INTRODUCTION

The concept of energy is one of the important topics in physics education, because it is the basis for understanding how energy is maintained, transformed, and used in various systems. A good understanding of energy conservation, kinetic energy, and potential energy is essential for students to master the basic principles of physics (McDermott & Redish, 1999). However, various studies have shown that these concepts are often abstract, so students have difficulty in understanding them well.

This difficulty affects students' learning interest and academic performance in physics subjects (Sadaghiani, 2011; Hake, 1998).

Learning the concept of energy often faces obstacles, especially in helping students visualize the relationship between kinetic energy, potential energy, and total mechanical energy in a system. Traditional learning approaches that are textual or lecture-based are often less effective in explaining abstract concepts (Kay et al., 2019; Li et al., 2022; Kantar & Sailian, 2018) . According to Hake (1998) and Redish (2003), learning methods that lack interactivity tend to produce shallow student understanding. Therefore, learning media are needed that not only support clear visualization of concepts but also encourage students to actively explore and understand the relationships between physics variables.

Computer-based simulations have been recognized as one of the most effective ways to solve this disparity. PhET Interactive Simulations created Energy Skate Park, an interactive simulation that lets students see how kinetic energy, potential energy, and total mechanical energy change in real-life scenarios (Perkins et al., 2006). In addition to providing easy-to-understand visualizations, this simulator allows students to conduct virtual experiments that enhance their understanding of energy principles. A skater's movement on a semicirculartrack shows in Figure 1, where energy changes dynamically as the skater moves.

Figure 1. Skater Movement on a Semicircular Track
Source: Perkins et al. (2006)

Research exploring the use of PhET simulations in physics learning has been extensive, but some previous studies tend to focus only on the effectiveness of simulations as a learning aid without exploring their impact on understanding energy concepts in depth. For example, Sadaghiani (2011) emphasized the benefits of simulations for increasing student engagement, but did not discuss in detail how simulations affect understanding of the relationship between kinetic and potential energy. Other studies, such as that by Wieman et al. (2010), highlighted the benefits of interactive simulations in teaching physics concepts, but did not explicitly evaluate their impact on understanding the concept of mechanical energy.

By thoroughly assessing how well the Energy Skate Park simulation teaches students about mechanical energy, our study aims to close this knowledge gap. The way in which this simulation aids students in mastering variations in kinetic energy, potential energy, and total mechanical energy in an ideal mechanical system is examined experimentally (VandenPlas et al., 2021; Iyamuremye et al., 2023; Subramanian et al., 2022). This study also seeks to determine how simulation aids in the growth of students' critical thinking abilities in the analysis of energy changes. This is consistent with the findings of Adams et al. (2008), who found that PhET simulations are more effective than traditional learning methods at enhancing students' conceptual knowledge.

This study has important significance because it not only provides empirical evidence on the effectiveness of computer-based simulation as an interactive learning medium, but also offers practical solutions to improve the quality of physics learning in schools. The results of this study are expected to support the development of innovative learning media that can facilitate students' understanding of abstract physics concepts, especially the concept of energy, and strengthen the role of technology in the learning process (Perkins et al., 2006).

RESEARCH METHOD

Research Design

This research uses an experimental research method, assisted by the interactive PhET simulation to teach energy concepts to students, specifically kinetic energy, potential energy, and mechanical energy. The study utilizes the "Energy Skate Park" simulation developed by the University of Colorado Boulder, which can be accessed via the following link: Energy Skate Park Simulation.

Time and Place of Research

This research was conducted over one week during the 2024/2025 academic year at Madrasah Aliyah Negeri 2 Indramayu, located in Indramayu Regency, West Java, Indonesia.

Research Targets/Objectives

The target of this research is to evaluate the effect of using the "Energy Skate Park" simulation on students' understanding of energy concepts, particularly kinetic energy, potential energy, and mechanical energy.

Research Subjects

The subjects of this study are 33 students from class XI IPA (Natural Sciences), selected using purposive sampling. This technique was chosen because the students have a relevant academic background in physics, particularly energy concepts, which supports the efficient achievement of the research objectives (Fraenkel, Wallen, & Hyun, 2012; Creswell, 2014; Slavin, 2006).

Research Procedures

The following procedures were applied during the research:

1. Students accessed the "Energy Skate Park" simulation.
2. The simulation was configured as follows:
   a. The Graph option was enabled to display energy graphs.
   b. Friction was set to "None" by adjusting the Friction setting to the minimum.
   c. Gravity was set to 10 m/s², and the object mass was set to 75 kg.
   d. The Speed option was enabled to display speed, with the mode set to Slow or Normal.
   e. Energy graphs for Potential Energy, Kinetic Energy, and Total Energy were enabled.
3. Students started the simulation by pressing the arrow icon on the main screen.
4. Students observed and recorded changes in kinetic energy, potential energy, and total mechanical energy as the skateboarder moved across various positions and heights.

Instruments and Data Collection Techniques

This study utilizes a combination of observation sheets and structured worksheets to collect data on students' understanding of energy concepts. Pre-tests and post-tests were given to measure the change in students' conceptual understanding. The PhET simulation itself serves as an interactive teaching and learning tool, enabling the collection of experiential data through direct student interaction.

Data Analysis Techniques

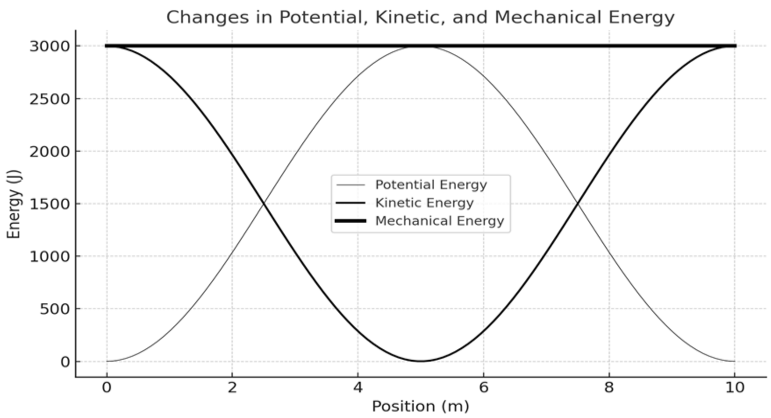
The quantitative data from the pre-test and post-test were analyzed using a descriptive statistical approach to evaluate students' understanding of energy concepts by comparing the scores before and after the intervention. This analysis aims to provide a more targeted understanding of the effectiveness of the simulation in the learning process (Fraenkel, Wallen, & Hyun, 2012; Creswell, 2014; Slavin, 2006).

This simulation gives students the opportunity to visually see how kinetic, potential, and mechanical energy change as a skater moves through various positions and heights. This direct method is very effective in helping students learn experientially, making it easier to understand abstract physics concepts (Finkelstein et al., 2005).

RESULTS AND DISCUSSION

Changes in Kinetic, Potential, and Mechanical Energy

The changes in kinetic, potential, and mechanical energy at various positions and heights as an object moves along a curved path.



Graph 1. The Relationship between Kinetic Energy, Potential Energy, and Mechanical Energy.

The graph 1 illustrates the relationship between kinetic energy, potential energy, and mechanical energy in a closed system without the influence of friction. Kinetic energy and potential energy exhibit an inverse relationship: kinetic energy increases as the object approaches the lowest point of its path, while potential energy increases with the object's height. Meanwhile, the total mechanical energy remains constant throughout the motion, reflecting the principle of energy conservation in a closed system free from friction or external forces.

The mathematical analysis of changes in kinetic energy, potential energy, and mechanical energy can begin by applying the fundamental energy equations in physics. In a closed system free from friction, the total mechanical energy (Emech) is the sum of the kinetic energy (Ek) and gravitational potential energy (Ep) at any point along the path.

At the highest point, potential energy reaches its maximum value, while kinetic energy is zero because the object's velocity at that point is also zero. As the object moves down the path, potential energy is gradually converted into kinetic energy, while the total mechanical energy remains constant in accordance with the principle of energy conservation. This relationship can be expressed mathematically as: Emech = Ek+Ep_

To determine the amount of kinetic energy (Ek), potential energy, and mechanical energy in various positions and heights, it can be found using the formula:

Ek = ½ mv2
Ep = mgh
where:
Emek = Mechanical energy (joule)
Ek = Kinetic energy (joule)
Ep = Potential energy (joule),
m = object mass (kg)
v = object speed (m/s2)
g = earth's gravitational force (10 m/s2)
h = height (m)

What is the value of speed at various positions and heights?

To calculate the speed at various positions and heights based on the Law of Conservation of Energy, the principle of mechanical energy can be used. At the highest point, the gravitational potential energy reaches its maximum value, while the kinetic energy is zero because the initial velocity of the object is also zero. According to Halliday, Resnick, and Walker (2013), when an object begins to move down the track, some or all of the gravitational potential energy is converted into kinetic energy, so that the speed of the object increases as the height decreases. This principle is in accordance with the Law of Conservation of Mechanical Energy, which states that in a closed system, the total mechanical energy remains constant (Serway & Jewett, 2018). Thus, potential energy and kinetic energy can convert to each other depending on the position of the object on the track. The calculation is as follows:

Ek = Ep (initial) - Ep (final)
$\frac{1}{2}mv^2$ = mgh (initial) - 0
$\frac{1}{2}mv^2$ = mgh, so $v = \sqrt{(2.g.h)}$
$v = \sqrt{2.10.4}$ m/s^2
$v = \sqrt{80}$ m/s^2
$v = 4\sqrt{5}$ m/s^2

Kinetic Energy

The kinetic energy at the highest point, where the object has not moved, is zero because the object's velocity at that time is also zero.

$Ek = \frac{1}{2}mv^2$
$Ek = \frac{1}{2}$ 75. 02 joules
Ek = 0 joules

The kinetic energy at the lowest point where the maximum velocity is $4\sqrt{5}$ m/s^2, then the amount of kinetic energy:
$Ek = \frac{1}{2}mv^2$
$Ek = \frac{1}{2}. 75. (4\sqrt{5})^2$
Ek = 3000 joules

Potential Energy
Potential energy at the highest position (6 meters)
Ep = m.g.h
Ep = 75.10.6
Ep = 3000 joules.

Potential energy at the lowest point (0 meters)
Ep = mgh
Ep = 75.10.0
Ep = 0 joules

Mechanical Energy

In ideal conditions without friction or air resistance, the change in kinetic energy and potential energy shows that the total Mechanical Energy at each Skate Park position remains constant. This principle is in line with the Law of Conservation of Mechanical Energy, which states that in a closed system without non-conservative forces, such as friction, the total mechanical energy will always be maintained (Halliday, Resnick, & Walker, 2014).

Mechanical Energy at the highest point
Emek = Ek + Ep
Emek = 0 + 3000 = 3000 joules

Mechanical Energy at the lowest point
Emek = Ek + Ep
Emek = 3000 + 0 = 3000 joules.

Relationship of Changes in Kinetic Energy, Potential Energy, and Mechanical Energy

Changes in kinetic energy, potential energy, and mechanical energy are visualized through the movement of a skater at various height positions, and this information is presented in detail in the table 1 below.

Table 1. Relationship of Kinetic Energy, Potential Energy, and Mechanical Energy at Various Skater Height Positions.

Energy (Joule)	Height Position (meter)				
	4	3	2	1	0
Kinetic energy	0	750	1500	2250	3000
Potential energy	3000	2250	1500	750	0
Mechanical energy	3000	3000	3000	3000	3000

The table 1 illustrates the relationship of changes in kinetic energy, potential energy, and mechanical energy at various height positions of a skater. The data presented shows the energy values in Joules at five different height points (4 meters, 3 meters, 2 meters, 1 meter, and 0 meters).

Kinetic energy is the energy possessed by an object due to its motion. At a height of 4 meters, the kinetic energy is 0 Joules, indicating that the object is at rest. As the object descends, its kinetic energy increases. At a height of 0 meters, the kinetic energy reaches 3000 Joules, which indicates the object is moving at maximum speed at the lowest position.

Potential energy is the energy an object has because of its higher position relative to a given surface. At a height of 4 meters, the potential energy is 3000 Joules, which is the largest amount because the object is at its maximum height. As the object descends, the potential energy decreases linearly. At a height of 0 meters, the potential energy is exhausted, reaching 0 Joules, because the object is at its lowest position.

Mechanical energy is the sum of kinetic energy and potential energy. The mechanical energy remains constant, which is 3000 Joules, throughout all positions of height. This shows that there is no loss of energy in the system, meaning that the total energy remains constant and only changes in the form of energy between kinetic and potential.

This phenomenon illustrates the principle of conservation of mechanical energy in an ideal system, where the total energy in the system remains constant even though the kinetic energy and potential energy change with each other as the object's position changes. When the object is at a height of 4 meters (maximum potential energy), the potential energy begins to decrease as the object descends, and this energy is completely converted into kinetic energy as the height decreases. When the object reaches a height of 0 meters, all potential energy has been converted into kinetic energy, which is reflected in the object's increasing speed. The mechanical energy that remains constant throughout the position indicates that there is no loss of energy in other forms, such as those caused by friction or other obstacles. Kinetic energy and potential energy together form mechanical energy. Throughout the height, the mechanical energy remains constant at a value of 3000 Joules, indicating that there is no loss of energy in an ideal system. The principle of conservation of mechanical energy states that the total energy in a closed system is always maintained, although energy can change form between kinetic and potential (Tipler & Mosca, 2014). When the potential energy is completely converted into kinetic energy at the lowest height, the system still satisfies the law of conservation of mechanical energy. The constancy of mechanical energy indicates that no energy is lost in other forms, such as friction or external resistance, so this system can be considered a closed system (Giancoli, 2014).

Does the angle of the point of movement affect the changes in kinetic energy, potential energy, and mechanical energy?

The angle of the starting point of movement does not affect the total mechanical energy or the initial potential of the system. However, the angle affects the kinetic energy and how energy is changed during movement. As long as the height of the starting point remains the same, the magnitude of the initial potential energy is not affected by the angle of the path. The sum of the potential and kinetic energy at a point is called the total mechanical energy (EM). The total mechanical energy is not affected by the angle of the path; because there is no initial kinetic energy, the total mechanical energy is equal to the initial potential energy (Em = initial Ep) when the object starts from rest (Tipler & Mosca, 2014).

The angle of the trajectory affects the acceleration of an object along the trajectory. This affects its velocity and kinetic energy during its movement. Since the component of gravity parallel to the trajectory is defined as $g.\sin\theta$, the acceleration along the trajectory increases with increasing angles (Young & Freedman, 2020). As a result, the object will move faster on a steeper trajectory, resulting in a faster increase in its kinetic energy than on a gentler trajectory (Serway & Jewett, 2018). Therefore, the angle of the trajectory affects the changes in kinetic and potential energy during movement along the trajectory. This is true even though at the highest point the angle does not affect either the total mechanical energy or the initial potential energy (Tipler & Mosca, 2014).

Students' Understanding of the Concept of Changes in Kinetic Energy, Potential Energy, and Mechanical Energy

The results of the study on students' understanding of the concept of changes in kinetic energy, potential energy, and mechanical energy are summarized in Table 2 below:

Table 2. The results of the study on students' understanding of the concept of changes in kinetic energy, potential energy, and mechanical energy

Data Type	Average	Standar Deviation	Change
Pretest	62.67	7.91	-
posttest	86.67	6.05	+24.00

The pretest and posttest results showed significant changes in students' understanding of the concepts of kinetic energy, potential energy, and mechanical energy. The pretest score had an average of 62.67 with a standard deviation of 7.91, indicating a fairly large variation in students' initial understanding. This shows that before learning, students' levels of understanding varied, with some students having low understanding while others had better understanding. According to Hake (1998), large variations in scores at the pretest stage reflect differences in the level of initial understanding among students, which is common in teaching new concepts.

After the intervention using the PhET Energy Skate Park simulation, the posttest score increased to an average of 86.67 with a standard deviation of 6.05. The smaller standard deviation at the posttest stage indicates that students' understanding became more even after learning. Although there was still variation, this difference was smaller compared to the pretest, indicating the success of the simulation in equalizing students' levels of understanding. This is in line with the findings of Creswell (2014), who stated that effective instruction can reduce variation in student scores, resulting in more uniform understanding.

The mean difference between pretest and posttest of 24 points reflects a significant increase in students' understanding. This increase indicates the effectiveness of using simulations in helping students understand energy changes. PhET simulations allow students to observe and understand energy changes visually and interactively, which contributes to increased conceptual understanding (Surjono & Suwono, 2014; Trundle & Bell, 2010). Thus, these results indicate that simulation-based learning is not only successful in improving students' understanding but is also able to unite their overall level of understanding.

The results of this study indicate that simulation-based learning not only succeeded in improving students' understanding but was also able to unify their overall level of understanding. This success can be attributed to several learning theories, such as constructivism, experiential learning, and multimedia learning. In constructivism theory, Piaget (1973) emphasized that learning is an active process in which students construct their own understanding through interaction with the environment. In this context, the PhET Energy Skate Park simulation allows students to explore the concept of changes in kinetic, potential, and mechanical energy interactively. By conducting virtual experiments, students can observe the results directly, build their conceptual schemes, and develop deeper understanding. In addition, Vygotsky's theory of social learning also supports the use of tools such as simulations to accelerate understanding through active interaction with learning media.

The theory of experiential learning developed by Kolb (1984) further strengthens the effectiveness of this simulation. According to Kolb, effective learning involves a cycle that includes concrete experience, reflection, abstract conceptualization, and active experimentation. In this study, the PhET simulation provides a concrete experience in the form of interactive visualization of energy changes, which allows students to reflect on and understand the law of conservation of energy. Through direct experimentation, students can develop these abstract concepts and apply them in various situations, so that the learning process becomes more meaningful.

Mayer's (2009) cognitive theory of multimedia learning explains that visual and interactive media can help students integrate verbal and visual information, improve retention, and facilitate transfer of learning. Simulations such as PhET Energy Skate Park provide graphics, animations, and visualizations of relationships between variables that allow students to understand abstract concepts more clearly. Thus, this simulation-based learning not only supports the formation of individual understanding, but also creates a more equitable and effective learning experience for all students. This shows that the combination of direct experience, active interaction, and interactive media can significantly strengthen the learning of energy concepts.

CONCLUSION

This study demonstrates that the law of conservation of mechanical energy applies in a closed system without external forces, as illustrated by the Energy Skate Park simulation. The total mechanical energy remains constant along the track, though kinetic and potential energy alternate in magnitude; kinetic energy peaks at the lowest point of the track, while potential energy is highest at the highest point. This reciprocal relationship exemplifies the conservation principle, where, in an ideal frictionless system, the total mechanical energy equals the initial potential energy when the object begins from rest. The track's angle influences the object's acceleration, causing kinetic energy to increase faster on steeper tracks, but it does not affect the total mechanical energy, only its distribution between kinetic and potential forms. The study reveals significant improvements in students' understanding of energy changes, with an average pretest-to-posttest score increase of 24 points, and more consistent understanding among students after learning. By providing a concrete and interactive experience, the simulation aligns with constructivist theory, emphasizing active exploration, experimental learning, and multimedia integration to enhance retention. This study contributes to visualizing energy transformations in a realistic and interactive manner, valuable for physics education, and suggests further exploration of non-conservative forces, like friction, to contrast ideal and non-ideal systems. The use of simulations such as PhET Energy Skate Park is recommended to deepen understanding of various system conditions, making abstract physics concepts more accessible.

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