The development of a simple solar energy heater as a stem based instructional material for high school students

H Kurniawati¹* and Triyanta²

¹ Master of Physics Teaching, Department of Physics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Indonesia
² Theoretical Physics and High Energy Laboratory, Theoretical Physics and High Energy Scientists Group, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Bandung, Indonesia

*Corresponding author: hanikurniawati@students.itb.ac.id

Abstract. This preliminary research aims to design instructional material for high school students. The research method used in this development is ADDIE (Analysis, Design, Development, Implementation, and Evaluation). The developed Instructional Material refers to the NGSS (Next Generation Science Standards)'s first dimension. Our design and development stage includes five parts, namely designing and building the equipment, applying the equipment to measure some physical quantities, data analysis, the effectiveness of teaching and learning, and developing lesson plan for teaching and learning. The result of the development is a comprehensive Simple Solar Energy STEM project lesson plan. This project could discuss various integrated topics, processes, or phenomena such as fusion process in a star, greenhouse effects, electromagnetic waves, alternative energy, thermal physics, and lenses which can be depicted in a concept map. The core competencies, time allocation, assessment, and concept map are incorporated into the lesson plan as part of the instructional material. The designed STEM heater project has discrepancies of 16% and 6.8% compared to advanced tools. These discrepancies are tolerable for educational purposes. The STEM Project is also applicable in every school as it is simple and the material is easy to find.

1. Introduction
Science, technology, engineering, and mathematics (STEM) education is an evolution of a U.S. government policy which was motivated by both the complex world problems such as climate change, resource management, water resources and motivation toward STEM [1]. This government policy was then developed and adopted by numerous countries [2,3].

In Indonesia, the STEM education term has gained a dramatic momentum among Indonesian educators with a rapidly increasing number of initiatives, thus highlighting the urgency to emphasise STEM Education [4–6]. While this may be true, much barrier still surrounds STEM Education and how to implement it in classrooms [7–11]. One of these barriers is the different interpretation of STEM Education. Due to these ambiguities, teachers continue to struggle to implement STEM Education at a classroom level [12,13].

Another barrier that has been identified is the teacher’s lack of preparation. A journal paper about the lack of preparedness in Indonesian High Schools clearly emphasises this [14]. The lack preparation of teachers is a result of two things; most teachers received training only in one discipline [13,15] and the lack of support materials for teachers in implementing STEM Education at a classroom level [16].
Without appropriate support materials, teachers will limit their ability to effectively integrate the four components of STEM Education [17].

A STEM support material can take the form of STEM learning instructional models. While the internet provides various STEM Projects which can be used as a support material, it lacks a relationship between content or discipline and sufficient material background [18]. Moreover, the projects obtained from the internet has to be effectively aligned and support the national curriculum.

One of the projects that are numerously found on the internet is solar power heater. The most basic design of this project is a closed box with aluminium foil covering the inner part of the box and a hole in the top covered by a transparent material. How well the heat stays inside the box will depend on the materials and design of the box. Even though this project may integrate many science topics, it lacks the background explanation and how the topics correlate each other on the internet. Consequently, from the present problem above, we investigate and design a STEM instructional material, a solar energy heater which supports the national education curriculum and has an interdisciplinary content relationship.

2. Method

The STEM instructional model is designed in the form of Rencana Pelaksanaan Pembelajaran (RPP, lesson plan). The research and development refer to the five stages of the ADDIE development model, but only three stages of the model are used in this preliminary research. The design and development stages include five sections which are designing and building the equipment, applying the equipment to measure and compute physical quantities, data analysis, the effectiveness of teaching and learning, and developing RPP for teaching and learning.

2.1. Design and building the equipment

2.1.1. Equipment design. The tools and materials needed by the students to create a simple solar power heater box will depend on their design. As for our design, the box was made primarily from Styrofoam with an outer size of 15 cm x 13 cm x 15 cm and an inner size of 10 cm x 8.5 cm x 11 cm. This was the smallest possible size that could accommodate a 50 ml water container and a thermometer while the focal point of the lens was on the water container. With a small size of the box, the Sunlight radiation coming into the box through the lens leads to significant temperature changes of water and air within the box and thus easily been observed. We use Styrofoam as the wall of the box and an aluminium foil as the inner cover of the box as they are good heat-insulating materials preventing heat from coming out of the system and thus creating an adiabatic system [19]. Note that the aluminium foil has a reflectivity of 88% [20]. We cut the upper part of the box to make a hollow of 5 cm in diameter for placing either a convex or a planar lens.

2.1.2. Real Problems. STEM education is usually related to some important real issues. And our STEM project corresponds to global warming and shortage of energy issues. Greenhouse gasses, e.g. carbon dioxide gas, which are the by-products of some human activities trap the heat so that it cannot escape from the atmosphere. The impact is a long-term increase in average air and ocean temperatures. In our model, the aluminium foil surrounding the inner wall of the styrofoam box plays the role of the greenhouse gas. Through this simple energy heater, students will learn the concept of a greenhouse, how does a sunlight warm the Earth, and how does the Earth’s greenhouse gases contribute to the temperature increase inside the house (the atmosphere) As for the second issue, the students will learn that the Sun’s radiation can be an alternative and renewable energy. In the future, hopefully, they will think of creating a way or equipment on how to use the Sun’s radiation energy creatively and effectively.
2.1.3. **STEM components.** The four STEM components related to the project design are shown in Table 1 as follows.

| STEM components | Description |
|-----------------|-------------|
| 1 Science       | This science project integrates many science topics, which are: electromagnetic radiation, heat transfer, fusion process inside a star, and optics. Each topic will then be elaborated individually to find their relationships and also be presented in the form of a concept map. |
| 2 Technology    | While creating the STEM Project, tools and materials are chosen wisely. Technologies are tools or equipment developed from scientific knowledge. Some example of technology we use: thermometer, stopwatch, convex lenses, and aluminium foil. |
| 3 Engineering   | The Engineering component in STEM project equipment design covering in this case cost, safety, aesthetics, size and effectiveness. |
| 4 Mathematics   | The Mathematics component of this STEM Project includes scale, geometry, arithmetic, graphs, and linear regressions. |

As shown in Table 1 above, this simple solar heater project relates four components of STEM Education and integrate many sub-disciplines or concepts which can be seen in the science and mathematics component analysis. This simple project also aims to accustom students in real-world problem-solving. In which sunlight can become an alternative solution for decreasing access to natural resources such as fuels.

2.1.4. **The crosscutting-concept analysis.** The Cross-cutting concept is a dimension of a framework from the Next Generation Science Standard (NGSS) which unifies the study of science and engineering through their standard application fields [21]. The seven crosscutting scientific and engineering concepts are analysed and shown in Table 2 as follows.

| Cross-cutting concept | Design Model |
|-----------------------|--------------|
| 1 Patterns            | Observe the pattern of the data in a graph and prompt questions about the relationships between physical quantities and the factors that influence them. |
| 2 Cause and effect    | The effect of light rays propagating into the box through a lens |
| 3 Scale, proportion, and quantity | The difference in scales and measurements in maintaining the heat inside the heater; the efficiency of the solar heater, and other physical quantities |
| 4 Energy and Matter   | Observe and track the flows of energy fluxes propagating into the simple solar heater system |
| 5 Stability and change | Observe temperature changes concerning time and energy flow |
| 6 Structure and functions | The structure of the box is chosen such that the focal point of the convex lens is on the water container resulting in a good function of the box for a water heater. |
| 7 System and system models | The box with a lens is a model of a simple solar heater. |

2.2. **Apply the equipment to measure physical quantities**

The designed equipment then was placed directly under the Sun. The sunlight then entered the inside of the box through the convex or planar lens and hit air and water molecules. The solar electromagnetic radiation energy then transformed into thermal energy and increased the temperature of air and water inside the box. We measured the temperature of air and water inside the box every two minutes. We measured these physical quantities for both convex lens solar heater and planar lens solar heater.
2.3. Data Analysis

The data plot acquire from the solar energy heater enables us to use a linear regression method to obtain, respectively, the change of water and air temperature per unit of time

\[ B_w = \frac{\Delta T_w}{\Delta t}, \quad B_a = \frac{\Delta T_a}{\Delta t} \]  

(1)

Utilising these results, we are then able to compute some other physical quantities such as heat flow into the water and air

\[ \frac{\Delta Q_w}{\Delta t} = c_w m_w B_w, \quad \frac{\Delta Q_a}{\Delta t} = c_a m_a B_a \]  

(2)

where \( c_w \) and \( c_a \) are specific heats of water and air respectively while \( m_w \) and \( m_a \) are masses of water and air, respectively. The Sunlight radiation intensity on the Earth’s surface \( I_E \) and the energy flowing out from the Sun in the form of electromagnetic waves per unit of time \( P_S \) can be computed according to

\[ I_E = \frac{\Delta Q}{A \Delta A t}, \quad P_S = 4\pi R^2 I_E \]  

(3)

where \( A \) is the area of the hole in the upper part of the box, \( R \) is the Earth-Sun average distance and \( \Delta Q = \Delta Q_w + \Delta Q_a \). Comparing \( I_E \) with results from other experiments using more precise equipment shows the accuracy of the measurement using this simple equipment. In fact, the accuracy of this experiment is not quite important in this case since the primary goal of designing this simple experiment is to help students understanding some physical concepts.

Now, using Einstein’s energy-mass equivalence \( E = mc^2 \) we then obtain the rate of mass loss of the Sun in term of electromagnetic radiation

\[ \frac{\Delta m}{\Delta t} = \frac{P_S}{c^2} = \frac{4\pi R^2 I_E}{c^2} \]  

(4)

Electromagnetic radiation of the Sun is polychromatic, consisting of electromagnetic waves with various frequencies and amplitudes. To give an idea of the value of the amplitude for the students, let us assume that the radiation is monochromatic with an amplitude of \( A \). As the intensity is a time average of the magnitude of the Poynting vector over a cycle it is proportional to the square of the amplitude [22]:

\[ I = \frac{A^2}{2\mu_0 c} \]  

(5)

Finally, students may learn the focal distance of a lens through an experiment with the convex lens.

2.4. Effectiveness of Teaching and Learning

Although this solar heater project is simple, it could integrate four STEM components and can be used to obtain values of some physical quantities directly and indirectly from the data collected. Thus this simple STEM project can be an entry point to discussion on some concepts in various topics, processes, or phenomena such as the fusion process in a star, greenhouse effects, electromagnetic waves, and lenses. These concepts are interrelated, and their relationship can be depicted in a concept map (Figure 1), a diagram that has an important characteristic called cross-links, where the relationship between concepts in different domains can be represented and seen in the map [23].
2.5. Develop a lesson plan for teaching and learning

2.5.1. Curriculum and Learning Materials analysis. The curriculum used in this research is the Indonesian national curriculum of 2013. It consists of core competencies which are the minimal learning competencies that must be achieved by the student for one subject in each education unit [24]. The core competencies and learning materials that are related to our STEM project are shown in Table 3.

| Core Competencies                                                                 | Learning Materials                                      |
|-----------------------------------------------------------------------------------|---------------------------------------------------------|
| Create sketches and technical drawings of product design.                          | Engineering (Year 7)                                    |
| Create a simple product using working equipment following the type, material, characteristics, and strength of the material. | 1. Sketch engineering                                   |
|                                                                                   | 2. Tools and their uses                                  |
|                                                                                   | 3. Types, properties, functions, strength characteristics of materials |
| Differentiate and determine the surface area and volume of a flat-side geometry (cubes, prisms, pyramid) | Flat-side geometry (Year 8)                             |
| Resolve problems related to surface area and volume of flat-side geometry (cubes, prisms, pyramid) and their combinations. | 1. Cubes, prisms, and pyramid                           |
|                                                                                   | 2. Nets                                                  |
|                                                                                   | 3. Surface area                                          |
|                                                                                   | 4. Volume                                                |
| Analyse linear functions (in straight line equations) and interpret graphs that are related to contextual problems. | Linear equations (year 8)                               |
| Resolve contextual problems related to linear functions as straight-line equations. | 1. Gradient                                              |
|                                                                                   | 2. Linear equations                                      |
| Apply the principle of measuring physical quantities, accuracy, precision, and scientific notation | Measurement (year 10)                                   |
| Present the results of physical quantities measurement and their accuracy using the right tools and techniques with scientific notation. | 1. Accuracy and Precision                               |
|                                                                                   | 2. Measuring instruments                                 |
|                                                                                   | 3. Measurement error                                     |

Figure 1. Concept Map of a Simple Solar Energy Heater
Analyse the effect of heat and heat transfer which includes thermal characteristics of materials, capacity, and heat conductivity of everyday life.

- Temperature, Heat, and Heat transfer (year 11)
  1. Temperature
  2. Heat Capacity
  3. Heat transfer by conduction, convection, and radiation.

Analyse the work of optical devices using reflecting and refracting properties of light by mirror and lenses.

- Optical instruments (year 11)
  1. Concave mirror
  2. Convex mirror
  3. Flat lens

Create a product which applies the principle of reflection and or refraction of mirror and lenses.

- Global Warming (year 11)
  1. The greenhouse effect
  2. The impact of global warming
  3. Energy efficiency
  4. Alternative energy sources

Analyse the process of global warming and its effect on life and the environment.

- Electromagnetic Radiation (year 12):
  1. Electromagnetic spectrum
  2. The source of electromagnetic radiation
  3. The use of electromagnetic radiation

Create a product which applies the principle of reflection and or refraction of mirror and lenses.

- Atoms (year 12)
  1. Core Structure
  2. Fusion reactions

Analyse the phenomenon of electromagnetic radiation, its use in technology, and its impact on life.

- Energy sources (year 12):
  1. Renewable and non-renewable energy sources
  2. Alternative energy

Presenting the benefits of electromagnetic radiation and its effects on everyday life.

Analyse the characteristics of an atom, radioactivity, its benefits impact, and protection in everyday life.

2.5.2. Analysis of effective week and time allocation. Effective week of learning [25] is used to analyse the time allocation needed in achieving each core competency. Limited time allocation can be handled by giving some part of the project outside the school.

2.5.3. Assessment Analysis. The three-domain of assessments is being analysed and developed on how it can be used as an instrument. The three-domain are cognitive, affective, and psychomotor. The cognitive domain is assessed using test and non-test instruments such as exam and written report. The affective domain uses four out of seven units which are tolerance, cooperation, politeness, and confidence. The psychomotor are assessed by using project-based assessment since a project-based assessment can involve several core competencies from the same subject or different subject [26]. These three domain competencies are being assessed through the whole STEM Project.

3. Result and Discussion
The product of this development research is a STEM Based Instructional Material which uses a simple solar energy heater to explain physics concept and phenomena. This project was limitedly tested to see its effectiveness to obtain the Sun’s temperature data. The data is then analysed, compared to another measurement result, and discern its relationship between other physics topics.

3.1. Data
The experiment was conducted in Bandung from 10:05 to 11:21 (GMT+7:00). We observed temperatures of water and air within the box every 2 minutes. Figure 2 shows the graph of the collected data.
3.2. Data Analysis

From Figure 2, we know that the water temperature in the convex lens solar heater is higher than that in the planar lens solar heater. While the air temperature within the convex lens solar heater is lower than that within the planar lens solar heater. This data shows qualitatively the work of a convex lens which is to concentrate the light from the sun at a focal point.

3.2.1. Heat flow and intensity. Based on the scatter plot of temperature versus time in Figure 2 and a linear regression method [27], we obtain the rates of change of temperatures of water and air: \( B_w = 0.26°C/s \), \( B_a = 0.27°C/s \). We then obtain the heat flow (power) and radiation intensity flowing into the water and air in the box as seen in Table 4.

|                  | Heat Flow \( \Delta Q/\Delta t \) (Watt) | Intensity \( I_E \) (Watt/m²) |
|------------------|-----------------------------------------|-------------------------------|
| Water in a convex lens solar heater | 0.942                                    | 479.68                        |
| The air in a convex lens solar heater | 0.02                                     | 10.19                         |
| Total            | 0.962                                    | 489.87                        |
| Water in a planar lens solar heater  | 1.04                                     | 532.98                        |
| The air in a planar lens solar heater | 0.02                                     | 10.19                         |
| Total            | 1.06                                     | 543.17                        |

Note: The radius of the hollow is 2.5 cm

3.2.2. Comparison of measurement result. When compared with other person’s measurement using more advanced tools, it was found that the value of intensity in Bandung [28] area is 50 Cal/cm² for one hour from a range between 10:00 to 11:00 or at approximately 583 watts/m². So the discrepancies with results in [28] are 16.0% for the convex lens solar heater and 6.8% for planar lens solar heater. The discrepancies are tolerable for education purposes.

3.2.3. Radiative mass loss of the Sun. Since the radiation energy from the Sun is evenly distributed on the sphere’s surface of radius \( R = 149,600,000 \) km, the average distance between the Sun and the Earth the intensity obtained from the planar lens solar heater gives the energy radiated by the Sun per second in the form of electromagnetic waves is \( 1.64 \times 10^{26} \text{ Js}^{-1} \) which is equivalent to the \( 1.82 \times 10^9 \text{ kgs}^{-1} \) mass loss in the form of electromagnetic waves. This shows that the Sun loses 1.82 billion kilograms of its mass every second in the form of electromagnetic radiation. Of course, the real mass-loss is much greater than the above value since in addition to electromagnetic radiation the Sun also produces solar energy.
winds in the form of particles such as protons, neutrons, neutrinos, and others. The radiation originates from fusion processes within the core of the Sun.

3.2.4. Electromagnetic wave radiation amplitude. Assuming monochromatic, the amplitude of the electromagnetic radiation wave of the Sun is \( A = 857.7 \, Vm^{-1} \), using the value of \( I_E \) obtained from the planar lens solar heater.

3.2.5. Greenhouse. A Greenhouse is a process by which radiation from a planet’s atmosphere warms the planet’s surface [29]. This project uses the same principle as a greenhouse in which sunlight passes through the glass and warms the inner part of the house. The greenhouse is designed to keep warm air inside, whereas the greenhouse “effect” is the increased temperature inside the house (atmosphere). Through this simple energy heater student will learn the concept of a greenhouse, how does sunlight warm the earth, and how does Earth’s greenhouse gasses contribute to the temperature increase inside the house.

3.3. Lesson Plan Development

The lesson plan developed supports the national education curriculum in which it uses the Indonesian national curriculum of 2013 with an allocation time analysis. It follows the first dimension of the NGSS Framework, namely, asking questions and defining problems, developing and using models, planning and carrying out investigations, analyze and interpreting data, using mathematics and computational thinking, constructing explanations and designing, engaging in argument from evidence, and obtaining, evaluating and communicating information [21].

The lesson plan uses six meetings with different time allocation, 90 minutes for the 4th and 5th meeting, and 45 minutes for the rest of the meetings. Throughout the STEM Project, the limitation of time allocation can be handled by giving some part of the project outside school. The assessment of the STEM project includes three domains of assessment which are cognitive, affective, and psychomotor. We use a project-based assessment for the psychomotor domains because a project-based assessment can involve several core competencies [26].

As for the cognitive domain, we used to test and non-test instruments. The test instruments used are in the form of pre-test and post-test to know the initial and final knowledge of the students while the non-test instruments are used in the form of group project report and are submitted by the end of the project. The affective domains which are assessed are tolerance, cooperation, politeness, and confidence. These aspects are assessed throughout the whole STEM Project when the students are working together among their group.

4. Conclusion

A STEM instructional material which uses a simple solar energy heater has been investigated, designed, and developed. The STEM project integrates the four component of STEM and uses interrelated concepts which are depicted using a concept map. This STEM project is simple but has advantages as it interrelates various topics, processes, or phenomena such as fusion process in a star, greenhouse effects, electromagnetic waves and lenses which are presented in the form of concept maps to see the relationship of each concept. We showed that the temperature data of water and air in the box measured at various times could be utilised to obtain some physical quantities. Thus, this simple STEM education project is implemented in schools, students will not only learn one particular science concept, but they will learn some but interrelated science concepts at once. This project is also applicable in every school as it is simple and the material used is easy to find. The designed STEM heater project has a discrepancies of 16% and 6.8% compared to advanced tools, but is still tolerable for educational purposes.
Acknowledgements
This work was supported by the Institut Teknologi Bandung under the P3MI research grant awarded to the Theoretical High Energy Physics and Instrumentation research division.

References
[1] Thomas B and Watters J J 2015 Int. J. Educ. Dev. 45 42–53
[2] Sanders M 2009 Technol. Teach. 68 20–7
[3] Breiner J M, Johnson C C, Harkness S S and Koehler C M 2012 Educ. Partnersh. 112 3–11
[4] Republika 2015 Indonesia Perlu Masukkan Aspek STEM dalam Pendidikan Online: https://republika.co.id/berita/pendidikan/eduction/15/03/08/nkyou7-indonesia-perlu-masukkan-aspek-STEM-dalam-pendidikan
[5] Zubaidah N 2017 Indonesia Perlu Mengembangkan Pendidikan Berbasis STEM Online: https://nasional.sindonews.com/read/1226155/144/indonesia-perlu-mengembangkan-pendidikan-berbasis-STEM-1501592293
[6] Syukri M, Lilia H and Subahan M M T 2013 Aceh Dev. Int. Conf. pp 105–12
[7] English L D 2016 Int. J. STEM Educ. 3 3
[8] Herschbach D R 2011 STEM Initiat. 48 96–122
[9] Kelley T R and Knowles J G 2016 Int. J. STEM Educ. 3 11
[10] Nelson T H, Lesseig K and Slavit D 2016 Making Sense of “STEM Education” in K-12 Context
[11] Sherhoff D J, Sinha S, Bressler D M and Ginsburg L 2017 Int. J. STEM Educ. 4 13
[12] Bybee R 2013 The case of STEM education: Challenges and opportunities. (Arlington: NSTA Press)
[13] Stohlmann M, Moore T J, Roehrig G H, Stohlmann M, Moore T J and Roehrig G H 2012 J. Pre-Coll. Eng. Educ. Res. (J-PEER) 2(1)
[14] Moore K and Yulianti K 2014 J. Educ. Technol. 1 49–67
[15] Honey M, Pearson G and Schwegingerb H 2014 STEM Integration in K-12 Education : Status, Prospects, and an Agenda for Research (National Research Council)
[16] Roehrig G H, Moore T J and Wang H 2012 Sch. Sci. Math. 112(1) 31
[17] Dare E A, Ellis J A and Roehrig G H 2018 Int. J. STEM Educ. 5 1–19
[18] Stefanich A and Munski L 2014 How to STEM: Science, Technology, Engineering and Math Education in Libraries ed V (Plymouth, UK: The Scarecrow Press, Inc) p 48
[19] Anone 2020 An Adiabatic Process is a Process in which No Energy as Heat is Transfered Online: https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Map%3A_Physical_Chemistry_(McQuarrie_and_Simon)/19%3A_The_First_Law_of_Thermodynamics/19.05%3A_An_Adiabatic_Process_is_a_Process_in_which_No_Energy_as_Heat_is_Transferred
[20] Hanlon J 1992 Films and Foils: Handbook of Package Engineering Chapter 3 (Lancaster, Pennsylvania, and technomic Publishing)
[21] National Research Council of the National Academies 2012 A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (Washington DC: The National Academies Press)
[22] Halliday D and Robert R 2013 Fundamentals of Physics (Wiley)
[23] Novak J D and Cognition M 2015 The Theory Underlying Concept Maps and How to Construct Them
[24] Menteri Pendidikan dan Kebudayaan Republik Indonesia 2016 Peraturan Menteri Pendidikan dan Kebudayaan Republik Indonesia Nomor 24 Tahun 2016 Tentang Kompetensi Inti dan Kompetensi Dasar (Indonesia)
[25] Dinas Pendidikan Provinsi Daerah Khusus Ibukota Jakarta 2018 Keputusan Kepala Dinas Pendidikan Provinsi Daerah Khusus Ibukota Jakarta Nomor 541 tahun 2018 (Indonesia)
[26] Kementerian Pendidikan dan Kebudayaan 2016 Panduan Penilaian oleh Pendidik dan Satuan Pendidikan Atas (Indonesia)
[27] Freedman D A 2009 *Statistical Models: Theory and Practice* (Cambridge University Press)
[28] Ermance H 1973 *Pengukuran Radiasi Matahari Global di Lembang* (Departemen Fisika Teknik, Institut Teknologi Bandung)
[29] Schneider S H 2001 *Global Climate Change in the Human Perspective* (Cambridge University Press)