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Article

Understanding Solar PV through the MinUS-C Module grounded in the ADDIE Instructional Model

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Abstract: The rapid advancement of renewable energy technology, particularly solar photovoltaic (PV) systems, necessitates improved knowledge and readiness for adoption among the younger generation. However, secondary school students often exhibit significant knowledge gaps regarding this technology, potentially hindering its future acceptance and usage. This study addresses this gap by developing the MinUS-C (*Minecraft Urban Solar Community*) learning module, grounded in the ADDIE instructional model, to systematically enhance students' understanding and readiness for solar PV technology. The module's design involved five phases of the ADDIE model: analysis, design, development, implementation, and evaluation. Findings from pre, post and delayed post-assessments reveal a marked improvement and retain in students' knowledge of solar PV concepts, such as electricity generation and PV system components, as well as their readiness to embrace this technology. The module effectively bridges the knowledge gap and fosters positive attitudes towards renewable energy adoption. This study contributes to educational literature by providing a structured, evidence-based module for promoting green technology literacy among secondary school students. The findings underscore the potential of integrating digital tools like the MinUS-C Module into science curricula to advance sustainable development goals, equipping students with critical skills and awareness for future energy transitions.

Keywords: ADDIE Model; Solar PV Technology; Renewable Energy; Module Development; Green Technology Literacy

Introduction

In the era of globalization and the urgent need to address climate change, the adoption of renewable energy technologies, particularly solar photovoltaic (PV) technology, is increasingly seen as essential for reducing dependency on fossil fuels. Solar PV technology holds significant potential in contributing to clean energy solutions, yet its integration into mainstream education remains limited. Research by Kaczmarczyk and Urych (2022) highlights that although secondary school students are aware of environmental conservation, their understanding of solar PV technology remains superficial. This gap is primarily due to the science curriculum's limited coverage of renewable energy topics, resulting in insufficient exposure to the technical aspects of solar PV technology (Buldur et al., 2020; García-Ferrero et al., 2021).

Such knowledge is vital for cultivating future generations that are equipped to contribute to reducing carbon emissions and promoting environmental sustainability. Studies by Revák et al. (2019), Riyadi et al. (2021), and Spangenberger et al. (2020) corroborate that most students encounter the importance of renewable energy only during secondary school. However, their exposure to the technical aspects of these technologies is minimal, which could hinder their future acceptance and application of such solutions.

Focusing on secondary school students in Malaysia is critical because this age group is at a pivotal stage where early exposure to renewable energy concepts can foster long-term awareness and acceptance. With Malaysia's increasing emphasis on transitioning to sustainable energy sources, preparing students to understand and embrace solar PV technology is essential for future workforce development in the renewable energy sector.

The MinUS-C Module, designed based on the ADDIE instructional model, introduces a novel approach by integrating digital game-based learning (Kersánszki et al., 2023; Muenz et al., 2023) to overcome practical and knowledge-based limitations in existing solar PV education. Unlike traditional modules or curricula that are often limited to theoretical knowledge, MinUS-C Module engages students through hands-on virtual simulations that mirror real-world applications of solar PV technology. This approach not only enhances technical understandingbut also encourages active engagement and acceptance of renewable energy, making it a pioneering tool in the field (Slattery et al., 2023).

Literature Review

Previous studies indicate that secondary school students often lack sufficient knowledge of the technical aspects of solar PV technology. This deficiency largely arises from the science curriculum, which offers minimal coverage of renewable energy topics, leaving students with limited exposure to the technicalities of solar PV (Buldur et al., 2020; García-Ferrero et al., 2021). Chien et al. (2021) argue that education on solar PV technology should ideally begin at the school level, as many studies show that low public acceptance of solar PV technology significantly hinders its dissemination and adoption (Alam et al., 2021; Lau et al., 2021; Malik & Ayop, 2020; Vaka et al., 2020).

Despite teachers' awareness of the importance of solar PV technology, they often face challenges in effectively teaching this topic due to a lack of suitable resources and teaching aids (Ferreira et al., 2020; Aripriharta et al., 2019; Chen & Lin, 2021). Key limitations include restricted access to instructional materials that are appropriate for students' developmental stages and a lack of resources in local languages. These obstacles impair teaching effectiveness and can lead to misconceptions among students.

To address these challenges, the development of the MinUS-C Module is grounded in two primary learning theories: Social Constructivism (Vygotsky, 1978) and Constructionism (Papert, 1991). Additionally, the Technology Acceptance Model (TAM) (Davis, 1989) is employed to gauge students' readiness and acceptance of this technology. Together, these frameworks establish a strong foundation for constructing the MinUS-C Module and offer insights into how this module can enhance students' knowledge and acceptance of solar PV technology.

i. The Social Constructivism Theory (Vygotsky, 1978)
   This theory posits that learning transpires when students engage with others within a supportive environment. This social interaction may encompass guidance from teachers, collaboration among peers, and problem-solving activities (Adepoju et al., 2020; Setlhako, 2019). Through this process, students are able to construct new knowledge with assistance from more experienced individuals or supportive peers. In the context of this study, the MinUS-C Module is employed to facilitate social interaction in learning about solar PV technology. The activities within the module serve to enhance students' knowledge of solar PV technology.
ii. The Constructionism Theory (Papert, 1991)
   This theory emphasises that students' existing knowledge can effectively contribute to the formation of new ideas when they are actively involved in creating tangible artifacts in the real world. Both Constructionism and Constructivism focus on the active creation of knowledge by students; however, Constructionism particularly stresses that students generate new knowledge through the making of artifacts (products) and sharing them with others. When students exchange ideas, a clearer understanding emerges in the process of producing artifacts. According to Parmaxi and Zaphiris (2015), learning by doing and engaging in constructive play are educational approaches that embody

the principles of Constructionism. In this study, students using the MinUS-C Module will be engaged in the creation of artifacts related to solar PV technology. This process not only enhances their understanding of solar PV technology concepts but also cultivates essential collaboration and communication skills integral to 21st-century learning.

iii. The Technology Acceptance Model (TAM) by Davis (1989)
This model is frequently employed to elucidate how the public adopts new technologies and systems (Muzi et al., 2021). Davis introduced this model to explain users' acceptance of novel technologies, grounded in a robust theoretical foundation. The model aims to provide a framework illustrating how external influences can shape internal beliefs, attitudes, and behavioural intentions. In the context of this study, external factors, specifically through the use of the MinUS-C Module, can influence secondary school students' readiness to accept solar PV technology, referencing the four constructs proposed by Davis (1989): perceived usefulness, perceived ease of use, attitude towards usage, and behavioural intention.

Methodology

This study employs a research and development approach, utilizing the ADDIE instructional model, as illustrated in Figure 1. ADDIE is a structured and systematic model in learning design, selected for its strong theoretical foundation and organized sequence of activities aimed at addressing educational challenges (Yusoff et al., 2019). It is designed to systematically develop learning resources that align with students' needs and characteristics. The ADDIE model consists of five distinct stages: (1) analysis, (2) design, (3) development, (4) implementation, and (5) evaluation.. Each phase of this model is meticulously followed to ensure that the MinUS-C Module developed not only meets the set objectives but is also relevant and appropriate to the needs of the students, particularly in the context of their knowledge and readiness to adopt solar PV technology.

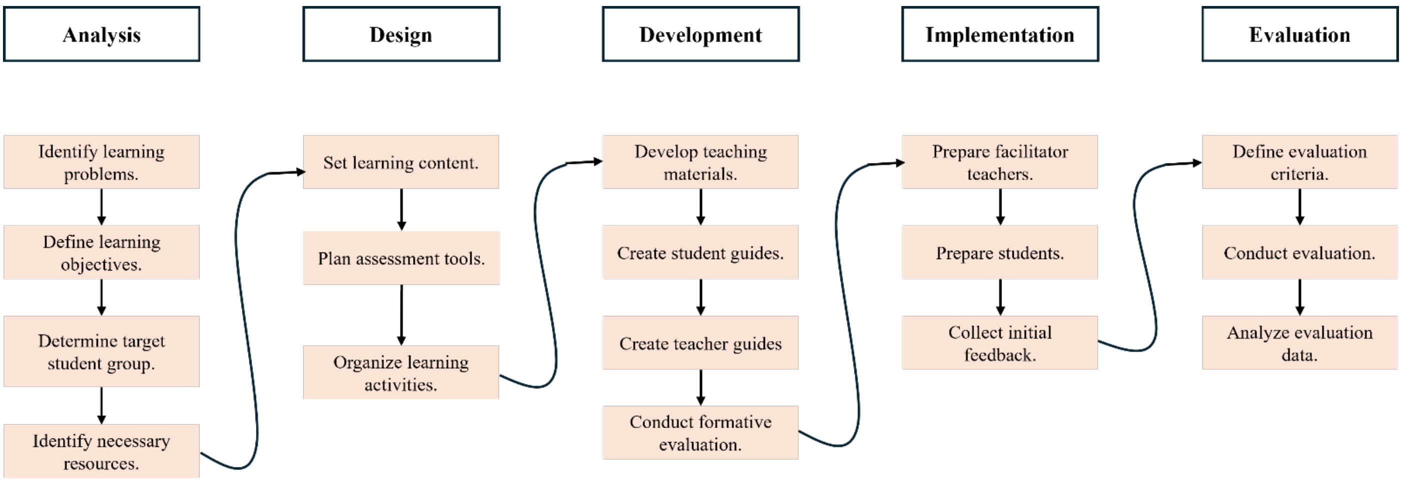

Figure 1. Procedure for developing a learning module based on the ADDIE model (Branch, 2009)

1.Analysis Phase

In this phase, a comprehensive needs assessment was conducted to identify students' knowledge gaps regarding solar PV technology, addressing both curricular limitations and existing misconceptions. Specific learning objectives were formulated to align with the module's aim of enhancing students' understanding and readiness to adopt solar PV technology. The target demographic was defined as secondary school students, and necessary resources, such as digital platforms and tailored instructional materials, were identified to meet the developmental needs of this group.

2.Design Phase

This phase involved creating a structured blueprint for the MinUS-C Module to address the established learning objectives systematically. Key content areas and technical aspects of solar PV technology were organized into a coherent instructional sequence, focusing on fundamental concepts necessary for understanding renewable energy. Assessment tools were designed to evaluate both knowledge acquisition and readiness, incorporating formative and summative measures aligned with the module's goals. Learning activities were planned based on social constructivist and constructionist principles, encouraging collaborative, project-based learning within Minecraft Education to simulate real-world applications of solar PV technology.

3.Development Phase

During the Development phase, instructional materials and guides for both students and teachers were created in alignment with the design blueprint. Student guides included step-by-step instructions for navigating the module and engaging effectively within the Minecraft Education platform, while teacher guides offered structured lesson plans and instructional strategies to facilitate effective teaching. Supplementary multimedia materials, such as instructional videos and worksheets, were developed to support interactive learning. A formative evaluation was conducted with a small pilot group, enabling iterative refinements based on feedback to enhance clarity, usability, and engagement.

4.Implementation Phase

This phase introduced the MinUS-C Module into an authentic classroom environment, engaging both facilitator teachers and students. Teachers received preparatory training to ensure familiarity with the module content and Minecraft Education tools, facilitating effective module delivery. Students were oriented to the learning activities and objectives, with guidance provided on using the digital platform. Initial feedback was collected from both teachers and students, offering insights that informed minor adjustments to optimize instructional efficacy during this initial implementation.

5.Evaluation Phase

In the Evaluation phase, the MinUS-C Module's effectiveness in achieving its educational objectives was assessed. Evaluation criteria, grounded in the module's learning objectives, focused on measuring students' conceptual understanding, engagement, and acceptance of solar PV technology. Data collection included pre, post and delayed post-assessments, surveys, artifact and focus group discussion, allowing for comprehensive analysis of the module's impact on students' knowledge and readiness. This data was analyzed to identify areas of strength and potential improvement, supporting a continuous enhancement approach to ensure the module's ongoing relevance and effectiveness for future applications.

Findings

1. Analysis Phase

The analysis phase aimed to investigate secondary school students' knowledge and readiness regarding solar PV technology. Several methods were used, including a literature review, document analysis, and interviews with science teachers, to identify gaps and challenges in teaching this technology. The systematic literature review revealed that secondary school students generally have limited knowledge about the technical aspects of solar PV, even though they recognize its environmental importance. A review of 22 articles published from 2010 to 2022 indicated that this gap in technical understanding is a widespread issue, relevant in various educational contexts. Document analysis of classroom-based assessments and topical tests further supported these findings, showing that most students displayed only moderate mastery of topics related to electricity, a foundational component for understandingsolar PV technology (see Table 1 and Table 2). This highlighted the need for a comprehensive educational approach to bridge these knowledge gaps.

Table 1. Distribution of survey participants by mastery level for the topic of electricity

Mastery Level	SMK X	SMK Y
TP 1	-	-
TP 2	-	3
TP 3	9	12
TP 4	12	6
TP 5	4	-
TP 6	-	-
Total	**25**	**21**

Table 2. Distribution of survey participants for topical test on the topic of electricity

Topical Test Score /10	SMK X	SMK Y
0 – 2 mark	2	5
3 – 4 mark	4	6
5 – 6 mark	7	9
7 – 8 mark	11	1
9 – 10 mark	1	-
Total	**25**	**21**

Semi-structured interviews with science teachers revealed additional challenges. Teachers reported that electricity and magnetism are difficult concepts for Form Two students to grasp, partly due to the lack of real-world connections and limited resources for teaching. Teachers also noted inadequate integration of technology into the curriculum, which hampers efforts to teach solar PV technology effectively. The interview findings (see Table 3) underscore the need for innovative teaching approaches and better support resources to enhance student comprehension and readiness.

Table 3. Summary of respondents' interview findings in the analysis phase

No.	Theme	R1	R2	R3	R4	R5	Frequency
1	Understanding complex scientific concepts	√	√	√	√	√	5
2	Use of technology in teaching	√	√	√	√	√	5
3	Challenges in integrating solar PV technology knowledge						
	- Financial resources	√	√		√	√	4
	- Learning time	√		√	√		3
	- Teachers' practical skills		√	√	√		3
4	Innovative learning approaches to improve knowledge of solar PV technology	√	√	√	√	√	5
5	Readiness to adopt solar PV technology	√	√	√	√	√	5

In summary, the analysis phase established a clear need for an educational module that not only improves students' technical knowledge of solar PV technology but also prepares them for its adoption.

2. Design Phase

Building on the analysis findings, the design phase centered on developing content, activities, and assessment tools for the MinUS-C Module. Key learning objectives were structured based on the Technology Acceptance Model (TAM) (Davis, 1989), focusing on perceived usefulness and ease of use to ensure relevance to students' readiness for solar PV technology. Content areas on electricity and solar PV were organized into a coherent instructional sequence covering essential concepts of renewable energy, specifically tailored to secondary school students.

Learning activities were designed to promote interactive and engaging experiences through Minecraft Education, encouraging students to explore solar PV applications in a simulated environment. This digital game-based approach aligns with Social Constructivism (Vygotsky, 1978), emphasizing learning through social interaction, and Constructionism (Papert, 1991), which focuses on knowledge creation through meaningful artifacts. These activities were structured to enhance readiness and knowledge by allowing students to collaboratively design and interact with solar PV components.

Table 4 outlines the artifact creation steps within the MinUS-C Module, using a sequence that combines the 5E instructional model (Bybee et al., 2006) and the social technology engagement model (Parmaxi and Zaphiris, 2015) to promote active learning.

Table 4. Steps for artifact creation in the MinUS-C module

MinUS-C Module	**Bybee *et al.*, 2006**	**Parmaxi & Zaphiris, 2015**
Knowledge Activation	Engage	Orientation / Brainstorming
Adventure	Explore	Material exploration
Modeling	Explain	Outlining
Augmentation	Elaborate	Editing Material
Refinement	Evaluate	Revising
Understanding	-	Peer & Instructor Reviewing
Launch	-	Presenting

The acronym "KAMARUL" (Knowledge Activation, Adventure, Modeling, Augmentation, Refinement, Understanding, Launch) is used to guide the artifact creation steps during activities with the MinUS-C Module as shown in Figure 2.

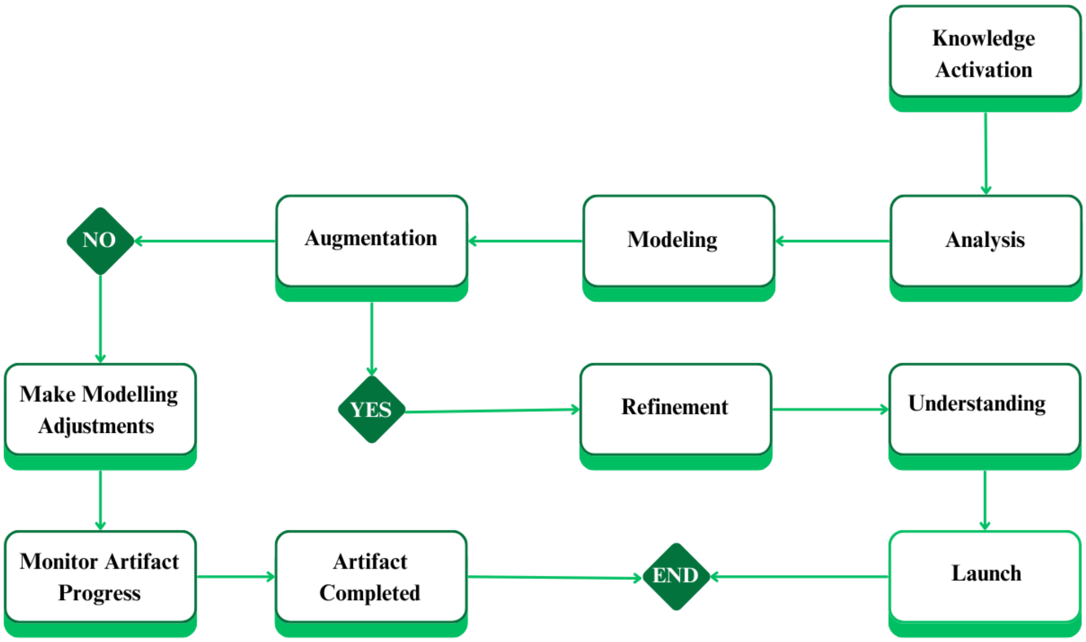

Figure 2. Flowchart of the artifact creation process

In summary, the design phase indicate that the MinUS-C Module has been meticulously planned to meet the prescribed learning content, utilizing an innovative and student-centered approach. This phase provides a solid foundation for the development of an effective module, which is expected to enhance students' knowledge and readiness to embrace solar PV technology.

3. Development Phase

In the development phase, teaching materials were created to support both students and teachers. This included the MinUS-C Module itself, instructional slides, videos, and other teaching aids. Each material was carefully aligned with the objectives established in the design phase phase to ensure clarity and coherence. Student guides provided step-by-step instructions on navigating the module and engaging with Minecraft Education, while teacher guides contained lesson plans and instructional strategies to aid in module delivery as shown in Figure 3. Supplementary multimedia, such as videos and worksheets, were also developed to enhance interactive learning. Figure 4 illustrates the learning domains covered, while Figure 5 presents the user manual for the Minecraft platform.

Figure 5. Front cover of the teacher and student guide

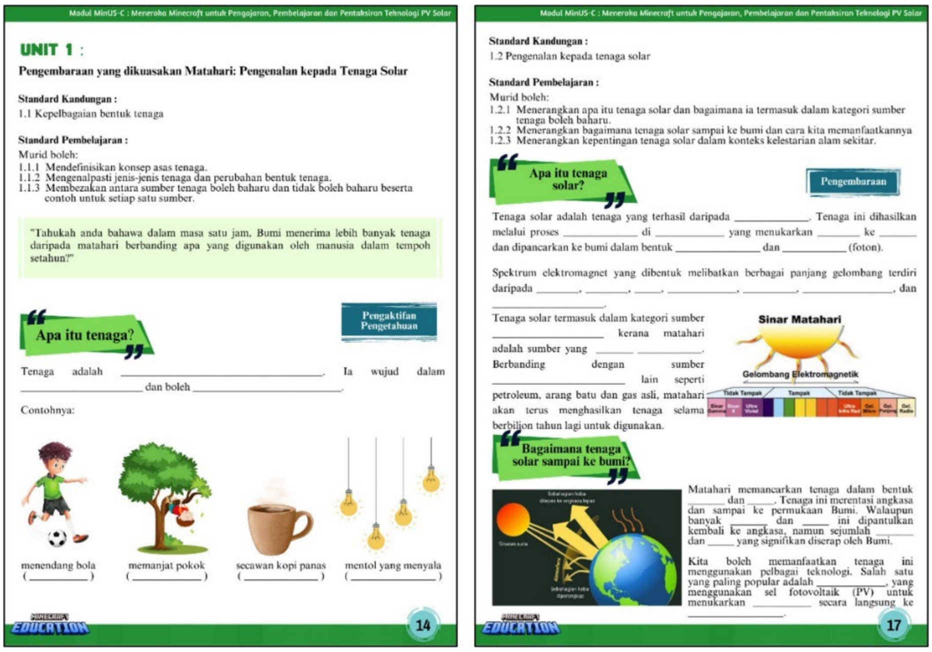

Figure 4. Learning domains in the MinUS-C module

Figure 5. User manual for the Minecraft Education platform

To ensure these materials met educational standards, an initial prototype was tested, and formative feedback was gathered from a small pilot group, leading to refinements that improved usability and engagement. Further validation was conducted with experts in science education, who reviewed the module for content validity. A high Content Validation Index (CVI) score of 0.91 was achieved, confirming the module’s alignment with learning objectives. Feedback from experts led to improvements in areas like content structure, visual design, and instructional flow to maximize effectiveness.

In summary, the development phase of this study ensured that the MinUS-C Module was carefully crafted, incorporating relevant expert evaluations to guarantee the quality and suitability of the module in achieving the learning objectives. This systematic and structured development process is crucial in ensuring the module’s effectiveness in enhancing students' knowledge and readiness towards solar PV technology.

4. Implementation Phase

The MinUS-C Module was piloted with two experienced STEM club teachers and 40 Form Two students. The 40 student participants were selected to mirror the demographics and educational level of the intended target group, providing a relevant and manageable sample size for a preliminary assessment of the module’s potential impact. This sample size was sufficient for the pilot study, allowing for in-depth qualitative feedback and preliminary quantitative insights to inform module refinement before broader implementation. Teachers, with over ten years of experience in science education, received training on the module content and Minecraft Education platform to ensure they could guide students effectively. Students completed pre-tests. and a readiness questionnaire to establish baseline knowledge and attitudes.

Over a two-week period, two of the module's seven activities were implemented, with teachers and students providing feedback on the structure and pacing. Teachers noted that the initial 60-minute duration was insufficient for students to fully engage in project creation. Consequently, activity time was extended to 80 minutes to allow students greater freedom to experiment and refine their solar PV simulations. Figure 6 depicts the pilot implementation process, showing students actively engaging with the module in a classroom setting.

Figure 6. Implementation of the MinUS-C module to pilot study participants

This feedback-based approach helped refine the module, ensuring it was well-suited to students' needs and practical for classroom application.

5. Evaluation Phase

The evaluation phase assessed the MinUS-C Module's effectiveness through both formative and summative evaluations. Formative evaluation was conducted throughout development and implementation, involving continuous feedback collection to refine module usability, pacing, and technical support. Classroom observations, Q&A sessions, and student-created artifacts provided insights into areas needing improvement, such as Minecraft Education training and extended activity time.

The summative evaluation, was conducted after module completion, focused on measuring the overall effectiveness of the module in enhancing students' knowledge of solar PV technology and their readiness to adopt it. Knowledge improvement was primarily assessed through pre, post and delayed post-tests administered before and after the module's implementation. The pre-test established a baseline of students' existing knowledge, while the post and delayed post-test measured knowledge gains and sustain, specifically targeting concepts such as electricity generation, solar energy principles, and PV system components. The results showed a statistically significant improvement in scores, which indicated the module's effectiveness in enhancing and retaining conceptual understanding. Additionally, to further evaluate students' understanding and application of solar PV knowledge, artifact analysis was employed. During the intervention, students created digital artifacts on the Minecraft Education platform that demonstrated their comprehension of solar PV technology. These artifacts were assessed on four criteria: knowledge of solar PV concepts, readiness to adopt technology (using NPC dialogue), effectiveness in PV technology simulation, and creativity. Each criterion was rated from 0 to 4, with higher scores indicating a deeper level of understanding and creativity as shown in Figure 7 and Figure 8.

Moreover, students' readiness to adopt solar PV technology was assessed through a structured questionnaire administered before and after the intervention. This questionnaire evaluated students' attitudes towards renewable energy, perceived importance of solar PV technology, and willingness to engage with related technologies. The positive shifts in responses highlighted an increased openness to adopting solar PV technology, suggesting that the module successfully fostered both knowledge and favorable attitudes. These findings were corroborated by delayed post-test assessments, which indicated that readiness acceptance improvements were sustained over time.

To complement the quantitative data, focus group discussions were held with students providing qualitative insights into the module's effectiveness. These discussions revealed strengths, such as interactive learning and the practical application of knowledge, and also highlighted areas for improvement, such as extending activity time and offering additional technical support. This feedback was invaluable in identifying further refinements to optimize the module. Overall, the evaluation demonstrated that the MinUS-C Module significantly enhanced students' knowledge of solar PV technology and their readiness to adopt it. The combination of pre, post and delayed post-tests and readiness questionnaires provided a comprehensive assessment of the module’s impact, while the qualitative insights from artifact analysis and focus group discussions offered a nuanced understanding of participant experiences. These findings affirm the module's success and provide a foundation for future improvements.

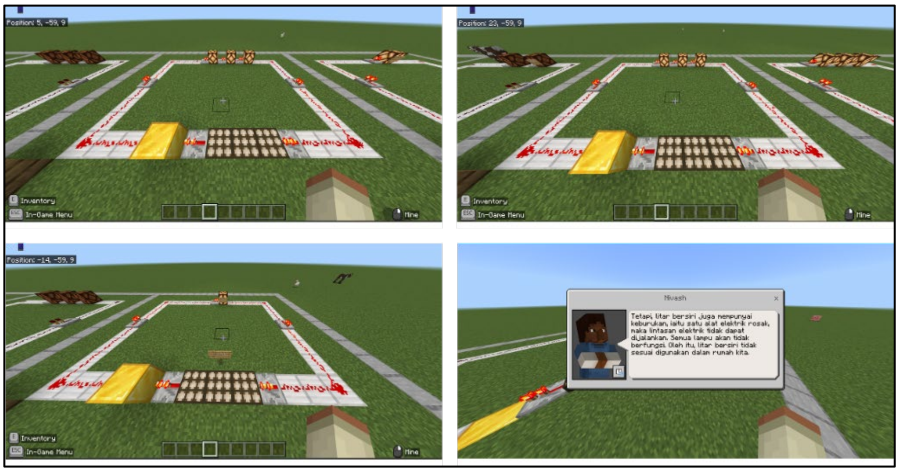

Figure 7. Example of artifacts produced by study participants for unit 4

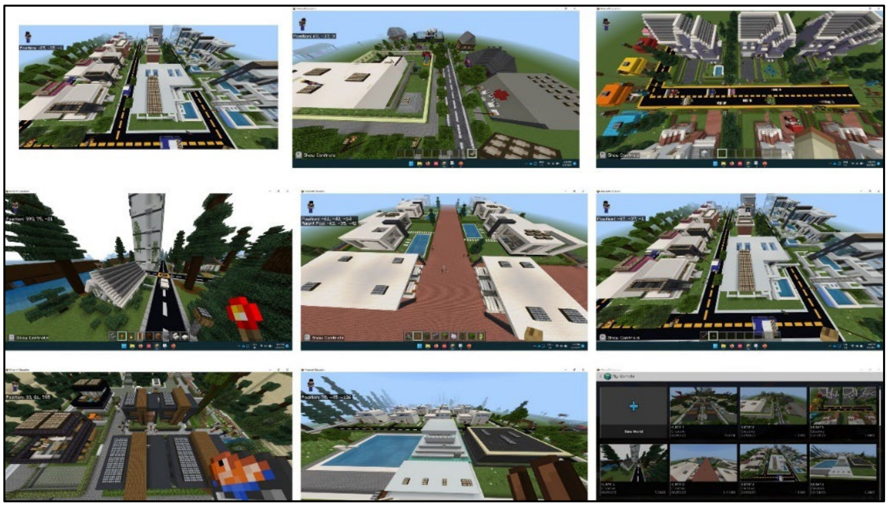

Figure 8. Example of artifacts produced by study participants for unit 7

Discussion

The development and implementation of the MinUS-C Module have demonstrated its potential to enhance students' knowledge and readiness to adopt solar PV technology, aligning with the study’s primary objective. Both formative and summative evaluations indicated that students significantly improved their understanding of solar PV technology, showcasing the module's effectiveness. However, certain areas, particularly time allocation and technical support, were identified as needing improvement.

One key challenge was the time constraint during Minecraft-based activities, which limited students' ability to fully explore, develop, and creatively apply solar PV concepts. The initial 60-minute duration was often insufficient for students to complete their projects effectively, impacting their engagement and learning effectiveness. To address this, the activity time was extended to 80 minutes, allowing students to delve deeper into their projects and refine their understanding. This adjustment provided students with a more thorough exploration of concepts, enhancing the learning process.

Another challenge involved the lack of familiarity with Minecraft Education among some students, which created a barrier to engaging with the module’s interactive elements. To facilitate smoother interaction with the digital tools, a preliminary tutorial session covering basic Minecraft skills was introduced, along with an inventory list of key Minecraft elements at the beginning of each activity. This additional guidance helped students navigate the platform more confidently, ultimately improving their learning experience.

Supporting literature underscores the importance of introducing renewable energy technology education at an early stage, given the generally low public acceptance of technologies like solar PV remains low (Alam et al., 2021; Vaka et al., 2020). The findings of the this study mirror these insights, as students initially exhibited limited knowledge of solar PV's technical aspects. While Ferreira et al. (2020) emphasized the need for teachers to relate complex technologies to students' daily lives, teachers in this study also encountered difficulties in integrating solar PV concepts into their lessons, highlighting a need for additional instructional support. The use of digital tools like Minecraft Education, although beneficial for engagement, requires structured support to prevent overwhelming both teachers and students.

The findings of this study have significant implications for the broader adoption of digital learning tools in science education, especially within Malaysia's curriculum. The MinUS-C Module facilitated active learning through game-based approaches and promoted critical thinking, illustrating the viability of integrating innovative methods into mainstream education. The module's alignment with the Technology Acceptance Model (TAM) highlights the importance of perceived usefulness and ease of use, which are essential factors in adopting new educational technologies. These factors are crucial for scaling the module across different educational settings, from urban to rural schools, as well as in diverse socioeconomic contexts.

For educators, the MinUS-C Module serves as an effective tool to engage students in complex scientific concepts like solar PV technology through interactive digital learning. The module's game-based nature helps students relate abstract concepts to real-world applications, increasing motivation and understanding. However, successful implementation requires adequate teacher training and support to ensure effective use of digital tools. Schools would need to allocate resources and provide teachers with access to both technology and training to maximize the benefits of modules like MinUS-C.

From a policy perspective, this study underscores the importance of comprehensive support systems during both development and implementation. For policymakers, the integration of the MinUS-C Module into the national science curriculum could serve as a strategic approach to advance renewable energy education and build environmental awareness among students. By embedding solar PV technology education early in students' academic journeys, policymakers can foster a generation that is more conscious of sustainable energy practices, which aligns with Malaysia's national objectives for achieving carbon neutrality. Furthermore, the module's inclusion supports Sustainable Development Goals (SDG), specifically SDG 4 (Quality Education) and SDG 7 (Affordable and Clean Energy), by providing high-quality, renewable energy education that is accessible and relevant to students' lives.

The MinUS-C Module also addresses the broader goal of reducing greenhouse gas emissions and promoting clean energy use, as envisioned in government policies on environmental sustainability. By equipping students with foundational knowledge about solar PV technology, the module helps to build a knowledgeable base of future consumers and advocates for renewable energy. This aligns with Malaysia's national commitments to sustainable development and provides a basis for future policies that integrate green technology education across different levels of schooling. The global implications of the MinUS-C Module are also noteworthy. Malaysia has the potential to set a benchmark in solar PV education through the widespread use of the MinUS-C Module, particularly within developing countries that share similar educational needs in renewable energy technology. This can enhance Malaysia's image on the global stage and create opportunities for international collaboration in education and technology. As an example of best practices in green technology education, the MinUS-C Module could inspire similar initiatives globally, promoting sustainable development and shared knowledge in the field of renewable energy education.

However, for broader implementation, practical challenges such as reliance on platforms like Minecraft Education and technological access limitations must be addressed. Ensuring that schools, especially those in rural areas, have the infrastructure to support digital learning is essential for equitable access to this educational approach. Policymakers need to consider investing in digital infrastructure and providing schools with adequate resources to facilitate digital learning modules, thereby ensuring that all students benefit equally from innovations like the MinUS-C Module.

Conclusion

The MinUS-C Module successfully achieved its objective of enhancing secondary school students' knowledge and readiness to adopt solar PV technology through an engaging, game-based learning approach. Designed using the ADDIE instructional model and grounded inSocial Constructivism and Constructionism, the module enabled students to interact with complex scientific concepts in a meaningful, interactive way. The positive impact on students' understanding of solar PV technology, supported by both formative and summative evaluations, confirms the module's effectiveness. However, areas such as time management and technical guidance require further refinementto optimize its use.

For future research, several directions can build upon the findings of this study. First, comparative studies across different educational settings, such as rural versus urban schools, could provide insights into how access to technology and socio-economic factors influence the module's effectiveness. Adapting the MinUS-C Module for use in rural schools, where digital resources may be limited, could offer valuable lessons in making renewable energy education more accessible. Research could also explore the module's adaptability to international settings, examining its potential application in other countries, particularly in developing regions that face similar challenges in promoting renewable energy literacy.

Another promising research direction involves integrating the module with emerging digital technologies like virtual reality (AR). These tools could further enhance interactivity and engagement, allowing students to experience immersive simulations of solar PV technology. This extension could foster a deeper understanding of renewable energy concepts and make the learning experience even more impactful.

Beyond the scope of renewable energy education, this study highlights the potential of digital tools like Minecraft Education to foster active learning and technological readiness within science curricula. For educational policymakers and curriculum designers, incorporating modules like MinUS-C into national curricula could be a strategic move to promote renewable energy literacy and prepare students for a sustainable future. To facilitate broader adoption, practical measures—such as teacher training, improved technology access, and sufficient learning resources—are essential. Aligning the module with national policies on digital and environmental education will further support sustainable development goals, helping to reduce greenhouse gas emissions and enhance Malaysia's standing on the global stage as a leader in renewable energy education.

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Conflicts of Interest: The authors declare no conflict of interest.

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